

The MAVEN Magnetic Field Investigation

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Abstract: The MAVEN magnetic field investigation is part of a comprehensive particles and fields subsystem that will measure the magnetic and electric fields and plasma environment of Mars and its interaction with the solar wind. The magnetic field instrumentation consists of two independent tri-axial fluxgate magnetometer sensors, remotely mounted at the outer extremity of the two solar arrays on small extensions (“boomlets”). The sensors are controlled by independent and functionally identical electronics assemblies that are integrated within the particles and fields subsystem and draw their power from redundant power supplies within that system. Each magnetometer measures the ambient vector magnetic field over a wide dynamic range (to 65,536 nT per axis) with a quantization uncertainty of 0.008 nT in the most sensitive dynamic range and an accuracy of better than 0.05%. Both magnetometers sample the ambient magnetic field at an intrinsic sample rate of 32 vector samples per second. Telemetry is transferred from each magnetometer to the particles and fields package once per second and subsequently passed to the spacecraft after some reformatting. The magnetic field data volume may be reduced by averaging and decimation, when necessary to meet telemetry allocations, and application of data compression, utilizing a lossless 8-bit differencing scheme. The MAVEN magnetic field experiment may be reconfigured in flight to meet unanticipated needs and is fully hardware redundant. A spacecraft magnetic control program was implemented to provide a magnetically clean environment for the magnetic sensors and the MAVEN mission plan provides for occasional spacecraft maneuvers – multiple rotations about the spacecraft x and z axes – to characterize spacecraft fields and/or instrument offsets in flight.

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45 I) Introduction

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47 The Mars Atmosphere and Volatile Evolution (MAVEN) mission seeks to understand the history of
48 climate change on Mars by studying the present state of the Mars upper atmosphere and ionosphere,
49 and the processes governing atmospheric loss to space [Jakosky *et al.*, 2014]. Mars has a thin and
50 dusty atmosphere comprised primarily of carbon dioxide (96%), argon (~2%) and nitrogen (~2%)
51 with traces of carbon monoxide, water, oxygen, and other gases. The temperatures and pressures in
52 the Mars lower atmosphere are comparable to those found in the Earth's stratosphere. With a
53 surface pressure of only about 1% of Earth's, and temperatures well below 273 K, it is difficult to
54 reconcile the thin atmosphere we see today with the geological evidence (channels, valley networks,
55 erosional features, small scale layering, and aqueous mineralogy) that suggest water flowed on Mars
56 until about 4 billion years ago.

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58 The preponderance of geologic evidence suggests that early Mars had a warm and dense
59 atmosphere and perhaps an ocean, if not standing water, persisting for a geologically significant
60 period. If so, where is this water today, and what became of the dense atmosphere? Mars is not so
61 massive as to trap volatile species indefinitely, so while loss processes remain poorly understood,
62 atmospheric loss to space is a prime candidate for their removal. Indeed, ample evidence of an
63 enrichment of heavy isotopes ($^{15}\text{N}/^{14}\text{N}$, $^{38}\text{Ar}/^{36}\text{Ar}$, and D/H) in the atmosphere [Jakosky and
64 Phillips, 2001; Mahaffy *et al.*, 2013] and direct measurements of escaping ions made by orbiting
65 spacecraft [Barabash *et al.*, 2007; Nilsson *et al.*, 2011] implicate loss to space as a significant, if not
66 dominant, loss mechanism throughout Mars history.

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68 The Mars atmosphere no longer enjoys the protection from the solar wind afforded by the presence
69 of a global magnetic field of appreciable magnitude. However, early Mars did have an Earth-like
70 magnetic field of sufficient strength to shelter the atmosphere from the solar wind [Acuña *et al.*,
71 1998; 1999; 2001]. So it is tempting to speculate that a warm and dense Mars atmosphere existed
72 within the protection afforded by an early Mars dynamo, and the demise of the dynamo, some 4
73 billion years ago, exposed the atmosphere to stripping by the solar wind. Had Mars retained a
74 dynamo, would it be more habitable today? To answer this question we need understand the
75 processes at work in the Mars atmosphere, and how to use that knowledge to infer the evolutionary

history of the atmosphere. There is also evidence for sequestration of water and possibly other volatiles in the Mars regolith, especially at mid and high latitudes.

The MAVEN spacecraft will spend more than a Mars year in polar orbit, sampling the Mars space environment with a full suite of in-situ and remote sensing instruments [Jakosky *et al.*, 2014]. These instruments are designed to provide the measurements necessary to characterize the upper atmosphere and ionosphere; quantify the current rate of escape of atmospheric constituents under a variety of solar wind conditions; and by backward extrapolation (more accurately, modeling) quantify the total atmospheric loss to space throughout Mars history. In looking back through time, we must bear in mind that our young Sun was likely far more active than at present, characterized by dramatically more violent outflows than we see today. The MAVEN prime mission is designed to observe the solar wind interaction with Mars during the declining phase of the current solar cycle, which thus far appears unremarkable but for a relatively weak sunspot activity.

II) Science Objectives

a. Mars Magnetic Field

The discovery of the intense magnetization of the Mars crust is one of the most remarkable findings of the exploration of Mars, and one of the most illuminating. The Mars Global Surveyor (MGS) mission established that Mars has no global magnetic field, and therefore no dynamo at present, but it must have had one in the past when the crust acquired intense remanent magnetization. It is likely that a molten iron core formed early, after or during hot accretion 4.5-4.6 Ga, and for at least a few hundred million years a substantial global field was generated by dynamo action in the core. The chronology proposed by *Acuña et al.* [1999] attributes the global distribution of magnetization to the early demise of the dynamo, prior to the last great impacts (~4 Ga) that left large unmagnetized basins in the crust. This view has been supported by more complete analyses of the large impact basins [Lillis *et al.*, 2008; Lillis *et al.*, 2013], leading to more precise estimates of the dynamo's demise. It appears that dynamo generation of the global magnetic field was extinguished before formation of Hellas and Utopia basins approximately 4.0-4.1 Ga.

109 Early onset and cessation of the dynamo is difficult to reconcile with the notion of a dynamo driven by
110 solidification of an inner core [Schubert *et al.*, 1992], the preferred energy source for the Earth's
111 dynamo. Alternatively, an early dynamo can be driven by thermal convection, with or without plate
112 tectonics, for the first 0.5 – 1 Gyr [Breuer and Spohn, 2003; Schubert and Spohn, 1990; Stevenson *et al.*,
113 1983; Connerney *et al.*, 2004], persisting as long as the core heat flow remains above a critical threshold
114 for thermal convection [Nimmo and Stevenson, 2000]. With knowledge that Mars had a substantial
115 global magnetic field billions of years ago, it is quite natural to consider whether the Mars atmosphere
116 may have been sheltered from the solar wind for a geologically significant period. In the dynamo era,
117 Mars may have retained a warm and dense atmosphere, only to lose it subsequent to decay of the global
118 field. Did the Mars dynamo prevent loss of atmosphere to space?

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120 There is also a supply side argument to be made on behalf of the Mars dynamo, if only indirectly. The
121 supply side argument follows from interpretation of the crustal magnetic imprint within the framework
122 of plate tectonics. A planetary dynamo is driven by vigorous convective motions in the core, resulting
123 from a temperature gradient across the core-mantle boundary. The thermal gradient persists as long as an
124 efficient cooling mechanism (e.g., mantle convection, and plate tectonics) is maintained. Following this
125 line of thought, the demise of the dynamo may be associated with cessation of plate tectonics. On earth,
126 we associate plate tectonics with active geological processes: crustal subduction, mantle convection,
127 active volcanism, and consequently venting of gases from the interior. This is the rationale for a supply
128 side argument: maintenance of a dense atmosphere via the active geologic processes associated with
129 mantle convection, subduction, and volcanism.

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131 After more than 2 full Mars years of mapping operations, MGS produced an unprecedented global map
132 of magnetic fields produced by remanent magnetism in the crust. This map (**Figure 1**) reveals contrasts
133 in magnetization that appear in association with known faults; variations in magnetization clearly
134 associated with volcanic provinces; and magnetic field patterns reminiscent of transform faults at
135 spreading centers [Connerney *et al.*, 2005]. Connerney *et al.* proposed that the entire crust acquired a
136 magnetic imprint via crustal spreading and cooling in the presence of a reversing dynamo; and that
137 erasure of this imprint occurred where the crust was buried (thermal demagnetization) by flood basalts
138 to depths of a few km. Transform faults are unique to plate tectonics, so if these features are indeed

139 transform faults then the Mars crust formed via sea floor spreading as on Earth [*Connerney et al.*, 1999;
140 *Sleep*, 1990].

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142 The magnetic record is complemented by geomorphological analyses that are suggestive of plate
143 tectonics having occurred on Mars early in its history. The alignment of the great volcanic edifices on
144 Mars is consistent with plate motion over a mantle plume [*Connerney et al.*, 2005] or, conversely,
145 volcanic chains formed above subducting slabs [*Sleep*, 1990 ; *Sleep*, 1994; *Yin*, *personal*
146 *communication*, 2012]. The topographical relief along much of the dichotomy boundary has been
147 interpreted as a series of ridge/transform fault segments [*Sleep*, 1994]. A recent structural analysis of the
148 Valles Marineris fault zone [*Yin*, 2012] likens this trough system to the left-slip, transtensional Dead Sea
149 fault zone on Earth: an undisputed plate boundary. It is difficult to understand how such a structure
150 evolved on Mars in the absence of plate tectonics.

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152 Is it possible that a warm and dense atmosphere on Mars was supplied by outgassing associated with
153 plate tectonics? If so, the Mars dynamo may have been instrumental in both the supply and maintenance
154 of an early dense atmosphere. The fate of Mars' atmosphere may well be inseparable from cessation of
155 plate tectonics and the demise of the dynamo; a marker for the evolution of Mars as a planet.

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157 b. Interaction with the Solar Wind
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159 Mars stands as an obstacle to the *solar wind*, the high velocity (supersonic) stream of plasma emanating
160 from the sun. The expanding solar wind drags the frozen-in *interplanetary magnetic field* (IMF) along
161 with it, and forms a multi-tiered interaction region about Mars as it interacts with the extended
162 atmosphere and electrically-conducting ionosphere (**Figure 2**). The characteristics of the
163 solar wind interaction with a weakly magnetized, or unmagnetized body are in some regards similar to
164 the flow about a magnetized planet [*Luhmann et al*, 1992; *Brain*, 2006], but for the lack of a global-scale
165 *magnetosphere* within which the motion of charged particles is governed by an intrinsic planetary
166 magnetic field.

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168 Since the solar wind is supersonic, a *bow shock* forms upstream of Mars (**Figure 2**). The slowed,
169 shocked solar wind flows around the obstacle within the *magnetosheath*, a turbulent region [*Espley et*
170 *al.*, 2004] bounded by the bow shock and a lower boundary, often referred to as the *magnetic pile-up*

171 *boundary* [Bertucci et al., 2003], or alternatively the *induced magnetosphere boundary* [e.g., Brain et
172 al., 2015] or *induced magnetopause*. It marks the narrow transition between plasma dominated by ions
173 of solar wind origin and plasma dominated by ions of planetary origin; it is often approximated by a
174 paraboloid of revolution about the planet-sun line. The magnetic field extends well downstream in the
175 anti-sunward direction, in effect draped around the conducting obstacle, to form the *magnetotail*, by
176 analogy with the magnetotail that forms downstream of a magnetic planet. A magnetic planet imposes a
177 geometry and polarity on the field in its magnetotail, whereas the magnetotail formed downstream of an
178 unmagnetized body changes direction in response to changes in the direction of the interplanetary
179 magnetic field.

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181 However, Mars is neither an unmagnetized body, such as Venus, nor a magnetized body, like Earth.
182 Where the Mars crust is intensely magnetized it can establish order over scale lengths of hundreds of
183 kilometers much in the way the Earth's field does. In the Earth's upper atmosphere and ionosphere, a
184 complex system of currents flow in response to solar heating of the atmosphere, particularly where
185 horizontal magnetic fields are encountered (equatorial fountain effect and electrojet), and in response to
186 the imposition of electric potentials (in particular, auroral ovals). By analogy to magnetized planets,
187 field-aligned currents, called *Birkeland currents*, flow along the magnetic field and deposit energy into
188 the electrically conducting ionosphere, particularly during solar storms, leading to auroral displays.
189 Auroral emissions have been observed on Mars [Bertaux et al., 2005; Brain et al., 2006; Lundin et al.,
190 2006; Brain and Halekas, 2012.] in association with the most intensely magnetized regions of the
191 southern highlands. On earth, and other planets with (dipolar) magnetic fields, auroral displays are most
192 often observed in the polar regions. In contrast, on Mars, auroral emissions are observed in association
193 with intense crustal magnetic fields that are strong enough to sustain magnetic fields to great heights,
194 well above the ionosphere. **Figure 3** illustrates the complexity of the magnetic field observed in a
195 meridian plane projection over the southern highlands, extending throughout the Mars upper atmosphere
196 and ionosphere. The MAVEN spacecraft will sample the magnetic field and plasma environment
197 throughout this region from about 120 km upwards, during "deep dip" campaigns and nominal orbital
198 operations.

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200 The crustal fields are strong enough to dramatically alter the nature of the interaction with the solar
201 wind, as can be seen in the multi-fluid magnetohydrodynamic simulation [Dong et al., 2014] illustrated

in **Figure 4**. Field magnitudes are appreciably larger in regions of strong crustal fields than they would otherwise be, creating “mini-magnetospheres” where charged particle motion is guided by persistent, and stable, magnetic geometries. The geometry imposed by strong crustal fields dictates where field lines threading the ionosphere link with the solar wind and distant plasma environments, giving rise to deposition of energy and aurorae. The strong crustal fields can also impose a polarity and geometry in the magnetotail as they are drawn tailward by the solar wind [Brain *et al.*, 2010]. Numerical simulations have amply demonstrated that the strong magnetic fields associated with the southern highlands have a shielding effect that reduces the ion escape flux [Ma *et al.*, 2004; Dong *et al.*, 2014].

In collisionless plasmas, waves provide one of the main ways of distributing energy across the system. Ion cyclotron waves are produced when ions move in resonance with the magnetic fields. This produces fluctuations in the magnetic field with frequencies that depend on the mass and charge state of the ions producing them. Additionally, the highly turbulent Martian magnetosheath offers an unusual plasma environment where nonlinear (i.e. $\delta B \sim |B|$) kinetic plasma modes develop [Glassmeier and Espley, 2006]. Some groups have examined the role that plasma wave heating may play in the escape of atmosphere [Ergun *et al.*, 2006; Andersson *et al.*, 2010] but this task will be easier once the full Poynting flux is available using data from both the MAVEN MAG and LPW instruments.

Magnetic reconnection is another important plasma process that may play an important role in bulk atmospheric escape [Brain *et al.*, 2010]. Magnetic reconnection may occur when anti-parallel (or nearly so) magnetic fields are brought together in a plasma, resulting in a localized exception to the frozen-in condition of the magnetic field. This allows magnetic fields to reconfigure (“reconnect”) and in the process magnetic energy is converted into thermal energy. Energization of the plasma can enhance atmospheric escape but the geometrical consequences of reconnection could be at least as important. The reconfiguration of the magnetic field may allow field lines that were connected to the IMF to lose that connection; conversely, reconfiguration may at times facilitate continuity with the IMF. Halekas *et al.* [2009] found many observations indicative of reconnection at Mars, suggesting that reconnection may not be uncommon. The first of its kind, fully instrumented particles and fields package (PFP) onboard MAVEN will allow careful investigation of this possibility.

The measurement of magnetic fields at Mars is therefore important to a variety of interrelated scientific topics, all bearing on the processes that control atmospheric loss to space. Characterizing the magnetic fields throughout the interaction region provides an interpretative framework to help us understand the complicated hybrid induced-crustal magnetosphere. In addition, the magnetic field magnitude and geometry are critical for understanding the trajectories of potentially escaping charged particles. The MAVEN Magnetic Fields Investigation plays an important role in understanding the role of plasma waves, reconnection, and bulk plasma structures in facilitating atmospheric escape and more broadly in the dynamics of the solar wind interaction.

III) Science Requirements

The magnetometer investigation (MAG) driving requirements benefit from a detailed knowledge of the magnetic field environment that MAVEN will transit, a consequence of the Mars Global Surveyor magnetic mapping. The MAVEN MAG requirements are sourced from the MAVEN Mission Requirements Document (MAVEN-PM-RQMT-0005), the MAVEN Level 3 Functional Requirements – Particle & Fields Functional Requirements Document (MAVEN-PFIS-RQMT-0016), and the MAVEN Magnetometer Level 4 Functional Requirements Document (MAVEN-MAG-RQMT-0061). The instrument requirements as follows:

- Measure the magnitude and direction of the ambient magnetic field;
- Provide the vector magnetic field (broadcast vector) to other science payloads in flight;
- Encompass a dynamic range of measurement from 3 nT to 3000 nT;
- Measurement accuracy & resolution of 1% or better;
- Sample rate providing temporal resolution of 20 seconds or better;
- Provide complete hardware redundancy of magnetic field measurement;
- Sensor orthogonality and alignment knowledge to 0.25 degrees or better;
- Provide non-magnetic a/c heaters for sensor thermal control, operating and non-operating.

Magnetometer Sensor Performance	
Sensor type	Dual tri-axial ring core fluxgates
Accuracy	0.05% absolute vector accuracy
Intrinsic noise level	0.015 nT (most sensitive range)
Attitude knowledge	Better than 0.05 degrees
Zero level stability	< 1 nT
Dynamic ranges (resolution)	512 nT (± 0.015 NT) 2048 nT (± 0.062 nT) 65536 nT (± 2.0 nT)
Intrinsic sample rate	32 vector samples/second
Radiation total ionizing dose (TID)	> 50 krad (at component level)

A more complete study of the magnetic field magnitudes that MAVEN may sample, between target altitudes of 125 and 400 km, was performed to optimize the choice of instrument dynamic ranges. Since MAVEN's mission plan does not target specific latitudes/longitudes, we need be prepared for the maximum field magnitude that might be experienced above the surface of the planet at altitudes in excess of ~100 km. This study demonstrated that it is very unlikely that a dynamic range of 512 nT might be exceeded throughout the entire mission, including the "deep dip" orbits. The magnetometer system provided as part of the Particles and Fields Package meets and exceeds the Project requirements with a pair of independent magnetic sensors with the following performance characteristics:

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IV) Investigation Design and Spacecraft Accommodation

a. Investigation Design

The MAVEN particles and fields instrumentation form an ensemble of instruments (“Particles and Fields Package”) controlled by a single hardware-redundant data processing unit (PFDPU) interfacing to the spacecraft. The PFP (**Figure 5**) services the Solar Wind Electron Analyzer (SWEA) instrument [*Mitchell et al.*, 2014], the Solar Wind Ion Analyzer (SWIA) instrument [*Halekas et al.*, 2014], the Langmuir Probe and Waves (LPW) instrument [*Andersson et al.*, 2014], the Extreme Ultraviolet (EUV) instrument, the Solar Energetic Particles (SEP) instrument, and the (STATIC) instrument [*McFadden et al.*, 2014] in addition to the Magnetometer instrumentation (MAG). The MAVEN magnetic field investigation (MAG) consists of two independent and identical fluxgate magnetometer systems that are interfaced to and controlled by the PFDPU. The particles and fields electronics package is a stack of individual electronics boxes (**Figure 6**) that service each of the instruments; two of the “slices” are occupied by identical magnetometer electronics frames that service the two magnetometer sensors. Each electronics box is fully shielded and each draws power from the redundant power supplies within the PFP.

Individual and independent a/c heater electronics assemblies provide thermal control for the MAG sensors and are also accommodated on separate cards elsewhere within the PFP. These are powered directly by the spacecraft, providing uninterruptable power for sensor thermal control regardless of the state (on or off) of the PFP. The a/c heaters are proportional controllers that maintain sensor temperature within comfortable operational limits. They are designed to insure that no dc currents can circulate in the resistive heater elements that are placed underneath the sensor base and within the sensor thermal blanketing. (The spacecraft heaters are direct current powered and are therefore not suitable for use in proximity with a magnetic sensor).

The magnetometer sensors are located at the very end of the solar array panels on modest extensions (.66 m in length) designated as MAG “boomlets”, placing them approximately 5.6 m from the center of the spacecraft body (**Figure 7**). Magnetometer sensors are best accommodated remotely, as far from spacecraft subsystems as is practical, to minimize the relative contribution of spacecraft-generated magnetic fields. Care is taken to minimize the magnetic signature of spacecraft

309 subsystems, of course, but one of the most effective ways to reduce spacecraft-generated magnetic
310 fields is to separate spacecraft systems and sensor, taking maximum advantage of the $1/r^3$
311 diminution of a magnetic (dipole) source with distance from the source. Thus magnetometer sensors
312 are often accommodated on a lengthy dedicated magnetometer boom that is deployed after launch.
313 Alternatively, they may be accommodated at the outer extremity of the solar arrays, taking
314 advantage of an essential appendage that also deploys post-launch. MAVEN took the latter
315 approach, much as its predecessor Mars Global Surveyor did [Acuña *et al.*, 2001].

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317 In typical implementations, a pair of magnetic sensors (“dual magnetometer technique”) provides
318 hardware redundancy as well as a capability to detect magnetic fields at two locations on the
319 spacecraft. This capability offers the potential to monitor spacecraft generated magnetic fields in
320 flight, by comparison of the field measured by each sensor. When both sensors are mounted along a
321 radius vector on a dedicated magnetometer boom, one “outboard” and one “inboard”, one can take
322 advantage of the $1/r^3$ diminution of the (dipolar) field of the spacecraft with distance along the
323 boom to identify local sources and separate the fields due to local sources from the ambient field.
324 The outboard sensor is typically allocated the majority of the spacecraft telemetry allocation for the
325 investigation, and sampled at a higher rate than the inboard sensor, anticipating a spacecraft field
326 that changes slowly in time (this is not always the case!). Thus the outboard sensor is the primary
327 sensor, and the inboard sensor is the secondary sensor, though in many implementations their role
328 may be reversed if desired.

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330 The MAVEN magnetometer sensors are located on the +Y spacecraft solar array (“outboard”) and
331 the –Y spacecraft solar array (“inboard”). The assignment is arbitrary, and in keeping with prior
332 missions (Mars Observer, Mars Global Surveyor) and software heritage; you may prefer to think of
333 the +Y sensor as the primary sensor, and –Y as the secondary sensor. In reality, they are identical,
334 and each sensor is capable of performing either role. It was anticipated that the +Y sensor
335 (“outboard” or primary sensor) location would be preferred over the –Y sensor location, from a
336 spacecraft magnetic interference perspective, by virtue of the location of various components on the
337 body of the spacecraft (reaction wheels in particular). Thus the +Y sensor was designated as
338 primary sensor (“outboard”), and –Y sensor as secondary sensor; observations of the magnetic field
339 during cruise operations confirmed this expectation. In early cruise, the inboard or secondary

sensor was sampled at a lesser rate, but as of June 2014, our current practice is to utilize the same sample rate for both sensors for diagnostic purposes.

b. Spacecraft Requirements

Instrument accommodation is always of concern for a magnetometer investigation, extending beyond the mechanical and thermal interfaces discussed above. Since the magnetometer sensors measure the ambient magnetic field, any appreciable spacecraft-generated magnetic fields may interfere with accurate measurement of the environmental field. The magnetic field produced by the spacecraft is managed via a spacecraft magnetic control plan that tracks the expected magnetic field at the sensor locations, and manages the net field at the sensors to meet a requirement appropriate to the mission. In recognition of the relatively weak field of the solar wind at Mars, the Project adopted a spacecraft magnetic field requirement not to exceed (NTE) 2 nT static and 0.25 nT variable. The static field is allocated a larger limit because with periodic spacecraft maneuvers a static magnetic field may be measured and corrected analytically.

c. Spacecraft Magnetic Control Plan

During the spacecraft design phase, and through assembly, test, and launch operations (ATLO), a magnetic model of the spacecraft was maintained as part of the spacecraft magnetic control program. This model accounts for the location and magnetic moment of spacecraft components and subsystems, and provides an estimate of the resultant spacecraft magnetic field, summed vectorially over its many parts, at the magnetometer sensor locations. The model is used to help allocate a fraction of the total NTE requirement to various subsystems and to guide mitigation where necessary. For example, when preliminary magnetic testing of the reaction wheel assemblies (RWA) indicated that they would contribute excessively to the variable (ac) spacecraft field, the Project responded with magnetic shielding enclosures for the RWAs that lessened their contribution by about an order of magnitude.

370 Spacecraft components, subsystems, and instruments were characterized by magnetic test at the
371 Lockheed Martin Waterton Canyon facility or at subcontractor facilities. Test articles included
372 engineering models that were available early in the program and for some subsystems and
373 instruments, flight or qualification models. The solar arrays were carefully designed with
374 compensation loops to null the magnetic signature of the array under illumination. This was
375 accomplished by compensating each individual cell string with a matched compensation loop on the
376 underside of the panel (“backwiring”). Verification testing of the solar array compensation scheme
377 was performed on a qualification panel tested at LM’s Sunnyvale facility. This test consists of
378 exciting the compensated string with a square-wave current and measurement of the resultant
379 magnetic field with a magnetic gradiometer, using synchronous detection to accurately determine
380 the response in an industrial environment. The actual flight arrays did not receive active magnetic
381 testing although the arrays and array extensions (“boomlets”) did undergo magnetic screening (with
382 a sensitive magnetic gradiometer) for magnetic remanence (magnetic “sniff test”). This testing is
383 done on the flight article, and any objects (hardware, thermal blankets, etc.) installed near the end of
384 the array, to avoid magnetic contamination near the sensor.

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386 The entire spacecraft underwent additional testing prior to shipment to the launch site. One test
387 (“swing test”) was performed to provide an estimate of the net spacecraft magnetic moment, and
388 another (“magnetic compatibility test”) was performed to measure the magnetic field produced by
389 systems and components when activated. The swing test, as the name implies, consists of measuring
390 the variation in magnetic field observed by a static magnetic sensor as the spacecraft, suspended at
391 the end of a lanyard, executed pendulum motion. This motion provides a clear periodic signal that is
392 easily distinguished from background in an industrial facility. A rotation test was also performed, in
393 which the suspended spacecraft was rotated in the presence of the magnetic sensor, to identify the
394 location of magnetically “hot” components. For the magnetic compatibility test, the magnetic field
395 was monitored as various subsystems were energized, to characterize the resultant magnetic
396 signature. During one of these tests, we identified dc heaters in the propulsion system that had not
397 been compensated properly; Project was able to reconfigure the operation of these heater circuits
398 prior to shipment to reduce the stray field to acceptable levels.

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400 V) Fluxgate Magnetometer

a. Instrument Description

The GSFC fluxgate magnetometer meets and exceeds the vector measurement requirement with a simple and robust instrument with extensive flight heritage. The MAVEN magnetometer design draws from Goddard's extensive flight experience, with over 78 magnetometers developed for space research and built at GSFC (e.g., Voyagers 1 and 2, Pioneer 11, Giotto, Lunar Prospector, Mars Observer, Mars Global Surveyor, MESSENGER, STEREO, WIND, ACE, AMPTE, TRMM, Freja, Viking, UARS, DMSP, Firewheel, MAGSAT, POGS, RBSP, and Juno). All are based on fluxgate designs developed by Mario Acuña at GSFC. The MAVEN sensors cover the modest dynamic range requirement with two instrument ranges that will be used in the Mars environment (+/- 512 nT and +/- 2048 nT full scale). The instrument also has a high range (65,536 nT full scale) that is useful in integration and test, permitting operation in ambient field in an Earth field environment without resort to magnetic shielding or nulling devices.

i. Principle of Operation

The fluxgate magnetometer is a simple, robust sensor capable of very high vector accuracy while requiring only modest resources [Acuña, 2002]. The principle of operation is illustrated with the help of the simplified schematic (**Figure 8**) that describes a generic, single axis fluxgate magnetometer utilizing a ring core sensing element. The sensing element is a high permeability ring formed by wrapping a thin tape of 6-81 molybdenum permalloy onto a non-magnetic Inconel hub. This material is nickel-iron alloy with about 81% nickel and 6% molybdenum content, the remainder iron, with a magnetic permeability of order 100,000.

The "fluxgate" works by driving this sensing element cyclically into saturation by exciting a toroidal winding at a drive frequency, typically about 15 kHz. The core saturation "gates" the ambient magnetic flux threading the sensing coil, as the core permeability alternates between very high, in the unsaturated state, and very low, in the saturated state. Core saturation occurs at twice the drive frequency, modulating the ambient flux at twice the drive frequency, and inducing a voltage in the sensing coil at $2f$, which is amplified and passed to a synchronous detector. The

synchronous detector is essentially a lock-in amplifier, using as a reference the second harmonic of the drive frequency, all derived from a stable crystal controlled oscillator. The output of the detector is fed back to the sense coil to drive the field in the sensor to zero, which results in a sensor with very high linearity. The output voltage is linearly related to the ambient field aligned with the axis of the sense/feedback coil. Several dynamic ranges may be implemented by selection of different feedback resistors using field effect transistors to perform the switching function.

A vector instrument (**Figure 9**) incorporates three single axis analog circuits like that shown schematically in **Figure 8**, or possibly four if a redundant axis is included. The three component (x, y, z) analog outputs are sampled by dedicated 16-bit Analog-to-Digital Converters (ADC) which are controlled by, and read by, a digital processor that formats the data for transfer to the PFPDPU, along with housekeeping data (temperatures, voltages, current measurements).

The MAVEN sensor (**Figure 10 and 11**) utilizes two ring core sensing elements, each of which sits inside of a pair of nested sense/feedback coils. This design uses the pair of orthogonal sense/feedback coils to detect both components of the magnetic field in the plane of the ring core, and to null the field in the plane of the ring core. Since each sensor element measures the field in two orthogonal directions, one may either have a redundant measure of the field along one axis or one may simply drive the redundant sense/feedback coil to null with the output from the companion sensor. The MAVEN magnetometers use this approach to null the field along the redundant axis. This design achieves superior linearity in strong fields relative to designs using single axis sense/feedback coils and it uses only two ring core sensing elements instead of the three required for a vector instrument otherwise. Each sensor assembly (**Figure 12**) is permanently mated to an optical cube that defines the reference coordinate system for the sensor.

ii. Analog Design

The FGM electronics (analog and digital) for each magnetometer are mounted in a single card frame in the PFP stack (**Figure 13**). The thermal controllers for the sensors are mounted back-to-back on a small circuit board stiffener (**Figure 14**) mounted elsewhere in the PFP (instrument interface board) to avoid the possibility of interference with sensitive analog circuitry. The MAVEN

magnetometer electronics were developed with many of the same electronics parts used for the Juno instrument, which was built to operate in a more demanding radiation environment; as such, the MAVEN instrument substantially exceeds the mission radiation requirement. The sensor assembly is passive and radiation tolerant.

A common drive circuit in the analog electronics drives the two sensor ring cores into saturation at a using a dedicated toroidal winding on each ring core. The ambient magnetic field in each sensor is sensed by synchronous detection of the second harmonic of the drive frequency, the presence of which reveals an imbalance in the response of the permeable ring core due to the presence of an external field [Acuña, 2002]. As with any fluxgate, care must be taken to insure that the spacecraft does not generate interference at harmonics of the drive frequency which could confuse the signal attributed as an ambient magnetic field. The two magnetometers operate independently, and to ensure that one does not interfere with the other, they are driven at different frequencies derived from the master clock. Flight model 1 (FM1) uses a drive frequency of 15.2 kHz, and flight model 2 (FM2) uses a drive frequency of 16.3 kHz. This results in ample separation of the second harmonic frequencies (30.4 kHz for FM1, 32.5 kHz for FM2).

The appropriate instrument dynamic range is selected, automatically, by range control logic within the field programmable gate array (FPGA), resulting in autonomous operation through the entire dynamic range. All range and instrument control functions are implemented in hardware. The FGM powers up in operational mode autonomously, sending telemetry packets to the spacecraft C&DH immediately without need of further commands. A limited command set allows us to tailor the science and engineering telemetry to available resources (via averaging and decimation of samples or packets) and to uplink changes in the parameters that control various functions as desired.

Power and Thermal Interface

Each magnetometer sensor board receives power from the PFDPU. There are two magnetometer boards in the MAVEN implementation and each board receives an independent power service from the PFDPU in order to maintain hardware redundancy. The magnetometer electronics requires +/-13V from the PFDPU service. The MAG electronics uses local linear regulators to produce the required internal voltages for analog VREF (+11.4V), current source (-8.5V), sensor analog to digital converters (+5V

495 and -5V), and digital logic levels (+3.3V and +2.5V). There is no EMI filter on the MAG board for the
496 +/-13V power supplied to MAG; this function is provided by the PFDPU power service.

497

498 The two magnetometer AC heater circuits require separate +28V supplies (+24V to +36V) and operate
499 independently and autonomously from the sensor electronics. These power lines pass through the PFP
500 but are powered independently of the PFP so that the MAG sensors are supplied with operational and
501 survival thermal power regardless of the state of the PFP. Each AC heater circuit operates
502 autonomously when the nominal spacecraft bus unregulated power is applied and requires no commands
503 or external configuration. The heater pulse width modulator (PWM) starts to activate at approximately
504 +30C and continues to increase power as the measured temperature drops to approximately -15C, at
505 which point the heater is fully on. The maximum power dissipated in the 80Ω heater is dependent upon
506 the (unregulated) power supply voltage.

507

508 The heater circuitry resides on a daughterboard resident on the power supply circuit board in the
509 PFDPU; it is physically separated from the MAG sensor electronics. A simplified block diagram of the
510 heater circuit is shown (**Figure 15**). The AC heater contains a transformer-coupled input that receives
511 3.3V level logic pulses from the DPU at a frequency of 131 kHz and a duty cycle of approximately 50%.
512 This is used to synchronize the AC heater pulse width modulation (PWM) circuitry to the PFDPU clock.
513 In the event that AC heater circuit power is on and the DPU clock is not present, an on-board oscillator
514 set close to the sync frequency will operate the PWM circuit. When the PFDPU is active, the heater
515 excitation frequency is synchronized to the PFDPU clocks. This is done to minimize interference with
516 other sensors (principally the Langmuir probe) on the payload.

517

518 Each magnetometer heater circuit provides a transformer-coupled heater monitor as an analog output to
519 the spacecraft. This service is provided in order to gain visibility into heater operation at times when the
520 PFP (and MAG) is powered off. The voltage output of the heater monitor is proportional to the power
521 dissipated in the 80Ω sensor heater resistance, providing an indirect measurement of sensor temperature
522 that is available in spacecraft telemetry.

523

524

525

iii. Digital Implementation

The MAG electronics requires only simple logic and does not require the capability and complexity of a microprocessor or software; it utilizes a single, low-power Field Programmable Gate Array (FPGA). The required logic is contained within a single radiation-hard Aeroflex UT6325 FPGA with +3.3V I/O. This design closely follows the Juno implementation, for which a very robust, radiation tolerant instrument was required. This FPGA provides an ample logic capability as well as internal radiation-hard memory. Aeroflex UT54ACS14E Schmitt-trigger inverters are utilized for signals that interface to the PDFPU.

MAG receives serial commands from the PFDPU digital control board (DCB) and returns telemetry to the PFDPU for further processing and/or transfer to the spacecraft command and data handling (C&DH) processor. The MAG board receives an 8.388 MHz clock (HFCLK) from the PFDPU ($2^{23} = 8,388,608$ Hz) which provides the global clock used by the FPGA. A derivative of this frequency is output to the analog sensor readout portion of the circuitry and utilized for resonant tuning of the magnetometer.

The 1.048 MHz CMD_CLK signal supplied by the DCB is used to shift in the CMD data from the DCB. The shift register outputs are synchronized internally to the main FPGA MAG_OSC clock prior to use by the MAG Command Processor logic. The MAG has several commands associated with instrument operation but does not require commands at startup to function. MAG does, however, require HFCLK and CMD_CLK to produce science telemetry in the nominal operating mode. The CMD_CLK is resynchronized to the internal HFCLK prior to use by the telemetry processor.

1. Data Modes

Each MAG electronics board communicates independently with the PFDPU, immediately upon application of power, and receipt of clock, without need for commands of any kind. The MAG telemetry consists of a block of telemetry sent every second to the PFDPU for further processing and/or transmission to the spacecraft. The MAG uses this single telemetry format to communicate science and engineering data to the PFDPU. This telemetry format consists of header information

(synchronization pattern, frame counter, spacecraft time information, and MAG status) as well as a block of science measurements (three components of the vector magnetic field in sensor coordinates at 32 vector samples per second) and a block of analog and digital housekeeping information. Upon receipt, and subject to ground command, the PFDPU selects a portion of this telemetry for retransmission to the spacecraft and ground, tailoring the output to meet telemetry allocations and science requirements.

The PFDPU may perform averaging and decimation of the native 32 vector samples/sec telemetry to achieve a desired telemetry allocation. Thus sample rates of 32, 16, 8, 4, 2, 1 vector samples/sec are available (independently) for each magnetometer. The PFDPU may also implement a simple 8-bit differencing scheme that offers a factor of two data compression, exclusive of the uncompressed header, for each instrument (independently). In our implementation, this data compression scheme is lossless: if any of the differences exceed the 8-bit dynamic range allocated, the uncompressed packet is transmitted instead. In both cruise and the Mars environment, this will occur (and indeed has occurred) very infrequently. The difference mode may be selected by ground command, relayed via the PFDPU; it has been used liberally throughout cruise to Mars.

2. Range Change Algorithm

Each MAG electronics card provides logic for autonomous operation of the magnetometer sensor, choosing an appropriate dynamic range (512, 2048, or 65,536 nT) depending on the environmental field. Alternatively, the instrument dynamic range may be commanded (manual mode) via an instruction passed to MAG via the PFDPU. Automatic range control is designed to work with minimal mathematics operations (lacking a microprocessor) by simple inspection of the three components of the measured magnetic field. The algorithm provides adequate hysteresis to prevent multiple transitions (“togglng”) in the vicinity of a threshold and uses a “look back” period to prevent multiple transitions during spacecraft rolls; it is based on the Juno algorithm.

Each MAG allows a change of dynamic range only at a packet boundary (once per second). The instrument range reported in the packet header thus represents the dynamic range of all samples

acquired in the corresponding one second interval. The MAG will range up (increasing dynamic range, decreasing sensitivity) in order to prevent saturation of individual axes. The ranging algorithm keeps track of how many times a measurement (in each component) exceeds a ranging threshold (**Figure 16**); if this count exceeds a (programmable) threshold, the instrument will range up at the next opportunity (packet boundary). This feature provides some noise immunity in that it makes it unlikely that a spurious measurement, or a few spurious measurements, will inadvertently trigger a range change.

Each MAG will range down (decreasing dynamic range, increasing sensitivity) to preserve as much measurement resolution as possible. Ranging down works in a similar manner, but threshold comparisons are made over a “look back” interval that is designed to encompass at least one spin period. This is used to prevent undesired range changes that would otherwise occur when all three components of the field drop below a threshold for only a portion of the spacecraft spin period. The MAVEN spacecraft is not a spinning spacecraft, but it is required to perform rotations about spacecraft principal axes from time to time to satisfy instrument calibration requirements.

The 512 nT dynamic range is anticipated to satisfy measurement requirements throughout the vast majority of the mission, including the “deep dip” campaigns that bring the spacecraft to lower altitudes. In this range, the 16 bit quantization provides more than adequate measurement resolution (± 0.015 nT), and a greater dynamic range would be required only if the periapsis during one of the deep dips occurred over a specific latitude and longitude corresponding to the most intensely magnetized site in the Mars crust. This is unlikely to occur unintentionally but the instrument has the capability to optimize the dynamic range should the very strongest field be encountered at periapsis during a deep dip.

iv. Radiation Environment and Parts Engineering

The MAVEN electronics parts radiation requirement is met by parts that are radiation tolerant to TID 13 krad (Si) @ 100 mil Al. Additionally, electronic parts are required to meet a LET threshold against latchup and SEE of $75 \text{ MeV-cm}^2/\text{mg}$ (or undergo further testing). Additional

details are available in the MAVEN Environmental Requirements Document, MAVEN-SYS-RQMT-0010. The MAVEN electronics design and implementation closely follows that of the Juno magnetometer investigation [Connerney *et al.*, 2014], which was designed for a more severe radiation environment (50 krad TID with a radiation design margin of 2). The MAVEN magnetometers were built from the Juno parts list and as such greatly exceed the MAVEN radiation requirement.

v. Performance

Performance of the magnetometers was monitored throughout the test program (Table) using a series of calibration procedures repeated before and after significant environmental tests. These calibration procedures are discussed below and in more detail in Connerney *et al.*, [2014]. FM1 preceded FM2 through development and thus had a more extensive series of calibrations.

A sensor with linear response may be characterized by the sensor model:

$$[B] = [A] \begin{bmatrix} s_1 (c_1 - o_1) \\ s_2 (c_2 - o_2) \\ s_3 (c_3 - o_3) \end{bmatrix}$$

Where the true field vector $[B]$ may be expressed as a linear combination $[A]$ of the sensor response; here $[A]$ is a nearly diagonal 3 by 3 matrix. The three components of the sensor response in counts (c_i) are corrected for small offsets (o_i) and scaled to magnetic units with scale factors (s_i). In practice we use near-unity s_i that are slight corrections to the nominal scale factors. The matrix A is often called the “orthogonality matrix” and it is a function of the sensor construction and alignment to the reference cube; it is used to express the measured field in the coordinate system defined by the reference cube normal vectors. We compared calibrations performed prior to and after vibration tests to demonstrate alignment stability to 0.03° or better. Similarly, across all environmental tests, scale factors for both instruments varied by less than 4×10^{-4} .

651 Table 1: Schedule of calibration activities throughout the environmental testing program.

652

FM1	Thinshell	Zeros	MAGSAT
23Feb12		√	√
28Feb12	√	√	√
12Mar12	√	√	√
14Mar12	√	√	√
March 13-21 Thermal Balance			
18Apr12		√	√
April 21-23 Vibration			
19Apr12	√	√	√
25Apr12	√	√	√
27Apr12			
May 2-10 Thermal Cycles			
14May12	√	√	√
15May12		√	√
FM2			
13Mar12	√	√	
March 13-21 Thermal Balance			
21Mar12		√	√
20Apr12	√	√	√
April 21-23 Vibration			
25Apr12	√	√	√
30Apr12			
May 2-10 Thermal Cycles			
15May12	√	√	√

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vi. Test Program

The MAVEN instruments followed the GSFC MAG group's standard laboratory setup and test procedure. The sensor bobbins and sensor assembly are thermally cycled over a wide temperature range for mechanical stress relief. The sensors are thermally cycled once from +75 °C to -35 °C

660 followed by 12 cycles from +60 °C to -20 °C. The magnetometer electronics progress through
661 resonant tuning of the analog input circuitry and frequency response verification, followed by
662 voltage, temperature, and frequency margin testing (VTFMT) in the lab. This involves
663 comprehensive functional testing at hot and cold temperature extremes (+80 °C to -40 °C) while
664 varying voltages and frequencies over their margined envelopes. The electronics and sensor were
665 also assayed for biological contamination prior to delivery.

666
667 The magnetometer electronics were integrated to the main electronics box of the PFP and
668 experienced environment tests as part of the PFP instrument suite including thermal vacuum,
669 thermal balance, the full array of electromagnetic compatibility tests, and vibration. Before and
670 after each test element, comprehensive end-to-end functional tests were performed to provide
671 system-level baselines for MAG. While it is not feasible to perform accurate magnetic calibrations
672 without access to the magnetic test site, functional performance and sensor noise levels were
673 established within two four-layer Mu-metal shield cans. These shielded enclosures were designed
674 to protect the sensors from physical damage throughout integration with the PFP at the University
675 of California, Berkeley, and later in the ATLO environment at Lockheed Martin's Waterton Canyon
676 facility in Denver. Each of the multilayer Mu-metal shielded enclosures was fitted with a computer-
677 controlled tri-axial coil system that was used inside the shield cans for both AC and DC stimuli.
678 This allowed full functional verification throughout integration and test at Lockheed's facility. The
679 magnetometer sensors were to be mounted, eventually, at the outer end of the solar panels, but
680 throughout much of ATLO the solar panels are not physically present. Therefore the sensors were
681 mounted atop the spacecraft buss, within their protective enclosures, to facilitate integration and test
682 while awaiting final assembly.

683 684 vii. Calibration

685
686 Calibrations of the MAVEN MAG instruments were performed on numerous occasions at system and
687 subsystem levels. We used subsystem level calibrations on the FGMs to establish performance
688 characteristics well in advance of system level calibrations. Later in development, when the Flight
689 Models (FMs) were available, system level calibrations were performed before and after each element of
690 the environmental test program (e.g., vibration, thermal vacuum) to establish that exposure to extreme
691 environmental conditions did not alter the instrument response to magnetic fields. At the system level,

our reference coordinate system is determined by the non-magnetic reflective optical cube affixed to each sensor. These small optical cubes (0.5 inch on a side) are fabricated to 10 arcsec orthogonality and all cubes were independently measured by the optics branch at GSFC. The magnetometer response is determined relative to this cube. Calibrations relative to the optical cube include both intrinsic sensor performance and the stability of the mechanical system that serves to bind all elements to each other.

Magnetic calibrations were performed at the GSFC Mario H. Acuña (MHA) Magnetic Test Facility (MTF), a remote facility located adjacent to the GSFC campus. The MTF includes a 22 foot diameter Braunbeck coil system (building 303), and associated control (building 304) and reference (building 309) structures, as well as other facilities. The 22 foot facility is sufficient to calibrate magnetometers to better than 100 parts per million (ppm) absolute accuracy for applied fields in all directions and field magnitudes up to about 1 Gauss. An independent measurement of applied magnetic fields is provided by Overhausen Proton Precession magnetometers (reference magnetometer) placed near the unit under test. The Proton Precession magnetometers provide an absolute measurement of the applied field over the dynamic range of about 20,000 nT to 1.2 Gauss (120,000 nT). The facility is operated in a closed loop with a remote reference vector magnetometer to null variations in the earth's field so applied fields may be held constant to a fraction of a nT over the duration of a calibration sequence.

Two independent methods were used to calibrate the MAVEN magnetometers. The vector fluxgates are calibrated in the 22' facility using a method ("MAGSAT method") developed by Mario Acuña for calibration of the magnetometer flown on the MAGSAT mission. This technique uses precise 90 degree rotations of the sensing element and a sequence of applied (facility) fields to simultaneously determine the parameters of the magnetometer model response as well as a similar set of parameters that describe the facility coil orthogonality [Acuña, 1981; a more accessible reference is *Connerney et al.*, 2014]. The method takes advantage of the accuracy with which the orientation of the sensor (reference optical cube) may be determined via autocollimation with a set of precision theodolites or alternately laser autocollimators. We used a pair of T-3000 theodolites permanently affixed to the coil facility structural members for this purpose. The method uses a sequence of applied fields of known magnitude aligned with the coil system symmetry axes (north-south, east-west, up-down) with the sensor oriented in a minimum of 3 orientations, as determined above, representing precise 90 degree rotations from the

initial orientation. All of the elements of the linear sensor response may be determined by inverting the resulting overdetermined linear system [Connerney *et al*, 2004].

The second calibration method, developed by the DTU researchers (called the “thin shell” method, alternately the “Orsted” method) uses a large set of rotations in a known and stable field to obtain much the same instrument parameters, subject to an arbitrary rotation [Risbo *et al*, 2002]. This method can be performed at a suitable (i.e., magnetically quiet) location using the earth’s field as a reference, simply by making a sufficient number of measurements of the vector field measured by the sensor in many orientations relative to the ambient field – thus the name: “thin shell”. This method also employs a Proton Precession reference magnetometer to measure the ambient field magnitude and account for any variations in the field during the test. Of course, this method can also be employed in a magnetic test facility at any desired field magnitude within the dynamic range of the facility. So we have also performed calibrations of the MAVEN magnetometers in our facility at several applied field magnitudes (which we call “thick shell” or nested thin shell calibrations) using this method; these may be performed relatively quickly.

The “thin shell” method by itself determines the magnetometer sensor response in an unknown coordinate system – an “intrinsic” coordinate system of the magnetometer sensor – the orientation of which needs to be determined by other means. This is equivalent to stating that the parameters of the linear sensor model may be determined subject to an arbitrary rotation, or, that only the symmetric part of the sensor response matrix is established via a “thin shell” calibration.

Sensor zero offsets are determined in the magnetic facility by physically reversing the sensor in a weak field, or by rotating the sensor in a weak (or zero) field. This may be done either in the center of the coil system, operated in nulling mode, or inside of a suitably demagnetized, multi-layer mu metal shield can.

b. In-Flight Calibrations

In-flight calibrations are designed to monitor stability of magnetometer offsets and to provide a capability to diagnose and monitor spacecraft-generated magnetic fields. In most applications, the magnetic sensors are fixed in the spacecraft reference frame, and a constant magnetic field in the sensor (sensor offset or bias) is indistinguishable from a constant (“static”) spacecraft-generated magnetic field. Thus it is common practice to lump them together and estimate the sum of the sensor offset and static spacecraft magnetic field. This may be done by performing spacecraft rotations in the environmental magnetic field.

i. Fluxgate Zeros and Static Spacecraft Field Determination

The mission plan allows for magnetic calibration maneuvers (roll maneuvers) that are scheduled to occur during the science collection phase approximately every other month, interleaved loosely with calibration maneuvers scheduled for the UVS investigation on a similar cadence. Two MAG calibration roll activities have already been conducted during cruise operations. Another set of MAG calibration maneuvers is scheduled to occur during transition orbit phase, and subsequent maneuvers will be scheduled throughout science phase. Care is taken to schedule the MAG calibration maneuvers to occur when (where) the spacecraft is more likely to experience a relatively benign environment – i.e., times and places where the magnetic field is more likely to be relatively quiet and not large in magnitude. For example, MAG calibrations will avoid periapsis where large variations in the magnetic field are expected and regions of near Mars space characterized by large field fluctuations (e.g., magnetosheath).

The periodic MAG calibration sequences (MAGROLLS) are designed to provide ~12 rotations about one axis, followed immediately by another ~12 rotations about a second sc axis. These execute at ~2 degrees per second rotation rate and each set of 12 rotations require about 42 minutes to complete. Prior to execution of the maneuver, a command is sent to reduce the spacecraft battery state of charge (SOC) to 80%, which effectively shuts off the solar arrays for the duration of the maneuver. This is done to eliminate the possibility of variable fields associated with solar array circuitry that might arise under variations of solar illumination angle (the subject of another set of in-flight tests). **Figure 17** shows the magnetic field measured during MAVEN’s second MAGROLL sequence performed on day 183, 2014. A set of rotations about two different axes is

sufficient to uniquely determine the combined sensor offsets/spacecraft field as long as the spacecraft magnetic field does not vary during the maneuvers. The rolls occur about the spacecraft principal moments of inertia, which depend on deployments, and are not aligned with the spacecraft payload coordinate system. For simplicity we refer to the roll axis closest to the spacecraft z axis as the “z axis” roll, and that closest to the x axis as the “x axis” roll. Inspection of the vector field during these rolls demonstrates that the rotation axes are not closely aligned with the spacecraft payload axes in the cruise (stowed) configuration.

We will use the term “offset” to describe the combined sensor zeros and spacecraft static field in what follows. We use a statistical least-squares estimation algorithm described by *Acuña* [2002] to estimate offsets. This method was developed to estimate offsets using the Alfvénic properties of the solar wind, that is, the observation that magnetic field variations in the solar wind tend to be variations in angular direction, preserving the magnitude of the field. The method works very well applied to spacecraft rolls where the variations in the vector field ought to preserve the field magnitude as well. The offset vector (\mathbf{O}) is obtained from a series of vector measurements ($i = 1, 2, 3, \dots, n$) of the magnetic field,

$$\mathbf{O} = [0.5 (\mathbf{B}_i + \mathbf{B}_{(i+l)}) \Delta \mathbf{B}_i] [\Delta \mathbf{B}_i]^{-1}$$

Where the difference $\Delta \mathbf{B}_i = \mathbf{B}_i - \mathbf{B}_{(i+l)}$ may be formed using sequential measurements of the vector field ($l = 1$) or measurements separated by l samples, chosen to provide a suitable vector difference $\Delta \mathbf{B}_i$, compared to measurement noise or instrument quantization step size, but not so large that variations in the field magnitude over l samples arise often. Applied to spacecraft rolls, l should be chosen to provide difference point pairs over a small fraction of a roll period. The inverse of the $3 \times n$ matrix $[\Delta \mathbf{B}_i]$ is obtained using the singular value decomposition method [*Lanczos*, 1961]. Mario *Acuña* obtained the result above simply by observing that differences in the measured vector field during a pure rotation of the field ought to be orthogonal to the ambient field, which is simply the measured field minus the offset. *Leinweber et al.* [2008] showed that this result may also be obtained by assuming that variations in the field magnitude are uncorrelated with the variance in differences of the three components. Simply stated, if the offsets are properly estimated, the measured field magnitude will not evidence a spin modulation as the spacecraft rotates [see also *Auster et al.*, 2002]. **Figure 18** shows the result of the offset estimation methodology applied to the

second MAGROLL maneuver obtained in cruise, which provides an estimate of the offset appropriate to that time (and the state of the spacecraft at that time). The MAVEN spacecraft will execute these maneuvers periodically, approximately every other month, as conditions dictate to monitor stability of the offsets over time. The current plan calls for these observations to be obtained in relatively low noise environments (solar wind, magnetotail), access to which is dictated by the orbital evolution and to some extent solar wind conditions. The latter are unpredictable on a time scale relevant to mission operations planning.

ii. Spacecraft-generated Magnetic Fields

Operation of the science instruments during cruise to Mars provided an opportunity to acquire instrument and subsystem calibration and performance data, exercise operations processes that will be required on orbit, and gain experience operating the instruments and the spacecraft. Operation of the magnetometers during the cruise phase also provides the first magnetic measurements of the spacecraft and systems, fully integrated and functioning in flight configuration, and operating in a low field environment. During cruise we noted spacecraft-generated magnetic fields of low amplitude associated with a few subsystems, notably thrusters (used infrequently after orbit insertion and orbital period reduction), reaction wheels, and the power subsystem (solar array circuits). The latter two sources are capable of producing fields of ~ 1 nT at the sensor locations, under some circumstances. The Project is actively investigating mitigation strategies to reduce or eliminate these effects during routine science operations.

The magnetic fields associated with the four reaction wheel assemblies appear at the (variable) frequency of operation of the individual wheels when their speed falls within the passband (0-16 Hz) of the magnetometers. The periodic signal from these sources is typically of low magnitude (0.1 – 0.2 nT) but has been observed to increase in magnitude at very low reaction wheel speeds. Project is currently evaluating a proposal to bias the reaction wheel speeds to higher RPMs during science operations to shift the interference above the magnetometers passband (or to as high a frequency as is practical).

847 We also observed variations in magnetic field associated with solar array operation that we have
848 identified with switching of one or more circuits residing on the outer solar array panels. We
849 originally detected a step variation in the field at the $-Y$ sensor location (~ 1 nT) and the $+Y$ sensor
850 location (~ 0.5 nT) during early cruise that occurred when the solar arrays were essentially switched
851 off via a command to reduce the state of charge of the batteries. An additional in-flight test is
852 planned prior to the start of science operations that will excite individual circuits on the outer panels
853 so we can uniquely identify the source and correct the field, analytically, using spacecraft telemetry
854 that identifies changes in switch state.

855

856

857 VI) Operations and Data Processing

858

859 a. Science Orbits Operations

860

861 The magnetometers were powered again on shortly after the Mars Orbit Insertion (MOI) maneuver
862 and they are to remain on throughout the mission. Orbital operations then largely of managing the
863 instrument sample rate to conform to the instrument telemetry allocation and planning spacecraft
864 maneuvers designed to diagnose and track any changes in spacecraft magnetic field and/or
865 instrument offsets. In late cruise and during early science operations, both instruments are being
866 operated at the same sample rate to assist in this process.

867

868 Current plans call for the magnetometer to sample at the high (32 vectors/s) rate throughout
869 periapsis (altitude less than 500 km) and at lesser rates throughout the rest of the orbit, subject to the
870 (time-variable) telemetry allocation. Telemetry allocations change throughout the mission subject to
871 practical limitations, such as the Earth-Mars distance and the number and frequency of downlink
872 opportunities afforded the Mission. In addition, the PFDPU collects and stores magnetometer data
873 at the highest rate continuously, and holds this data, along with that from the particle instruments
874 and the Langmuir and Plasma Wave Investigation, in memory aboard the spacecraft. This data
875 (“burst mode”) is available for downlink upon command, after an examination of the “survey” data
876 already downlinked. The concept allows the science team to decide how to allocate precious
877 telemetry resources (downlink at high time resolution the data that’s most interesting)

878 retrospectively, after a brief examination of the time series data downlinked at a lesser rate earlier.
879 Eventually the on-board memory is written over, making room for new burst mode observations.

880

881

882 b. Data Processing

883

884 Ground processing of magnetometer data is performed routinely at GSFC following downlink and
885 transmission to the Science Data Center (SDC) at the University of Colorado, Boulder. An
886 automated script at GSFC searches the database at the SDC for data files that have yet to be
887 downloaded, executing hourly. Files identified as such are pulled to the MAG operations computer
888 automatically and queued for immediate processing.

889

890 The MAG data processing is responsive to the need for rapid turn-around, since other instruments
891 require magnetic field vectors in their preliminary analysis, by design before spacecraft
892 supplementary engineering data is available for archive processing. A preliminary MAG data
893 processing pipeline (**Figure 19**) executes prior to receipt of reconstructed spacecraft ephemeris
894 (NAIF SPK kernels) and attitude information (NAIF C-kernels) necessary for archive processing,
895 and without benefit of engineering telemetry that may be necessary for detailed analysis.
896 Preliminary processing is conducted to assess the health and safety of the instrument, producing
897 time series magnetic field vectors in either sensor or spacecraft payload coordinates that are useful
898 in diagnosing instrument offsets and spacecraft-generated magnetic fields.

899

900 A similar but more comprehensive archive processing pipeline (**Figure 20**) incorporates
901 reconstructed spacecraft ephemeris and attitude information, and any supplementary spacecraft
902 engineering information, producing magnetic field vectors, and spacecraft position vectors, in a
903 variety of coordinate systems of interest.

904

905 Both processing pipelines utilize the same code which is designed to retain the ability to process
906 data when supplementary data is lacking for a complete analysis. The data flow is designed to be
907 extremely flexible in the ability to assimilate unanticipated observations, such as engineering
908 telemetry that may be desired for analysis, and not anticipated early in the mission. This facility is

implemented by utilizing a decommutated telemetry file that passes data to the main processing program in a text “keyword = value” format, originally developed for the Mars Observer and Mars Global Surveyor Projects.

i. Telemetry De-commutation

Raw binary MAG packets are checked for errors and decommutated using a bit map appropriate to the instrument mode (sample rate, differencing scheme if elected). Each data packet contains sufficient information within its header to allow processing of the data that it contains, from a magnetometer only perspective (i.e., excluding any spacecraft engineering data that may be required). The decom program produces a decommutated telemetry file (“.dtl” extension) that is an ASCII stream of “keyword = value” pairs, utilizing a text format similar to that employed by JPL’s NAIF text kernel readers.

ii. MAG Packet Processing

MAG packet processing operates on the dtl input files, converting instrument counts to magnetic field in nanoteslas, and engineering measurements in counts to engineering units, using calibration files for the instruments and conversion coefficients for engineering quantities (currents, temperatures, voltages, etc.). A SCLK (spacecraft clock) conversion file, provided by NAIF, is required to convert spacecraft clock words to Coordinated Universal Time (UTC), and a leapseconds kernel file (“leap.ker”), also provided by NAIF, is required to maintain accuracy of UTC time conversions. The input files may contain sensor data from either or both of the magnetometers, depending on whether the two (independent) data streams are merged, and as is the case in archive processing, may contain supplementary spacecraft engineering data (e.g., solar array currents, solar array switch states, etc.) for use in spacecraft magnetic field mitigation.

Archive processing adds access to reconstructed spacecraft ephemeris (SPK) and attitude information (C-kernels) that are delivered somewhat later than the instrument science data on a schedule dictated by Project. The Project currently envisions a weekly delivery of bested C-kernels, which are pieced together from a set of many smaller files that contain overlapping data in places,

abundant data gaps, and retransmission duplicates. The C-kernels are required to render spacecraft position and magnetic field vectors in the desired coordinate systems. These vectors appear in Cartesian coordinates on output records, one record per observation, at the highest time resolution available, for science data archive. Archive processing may also include spacecraft supplementary engineering data, merged with the instrument science data in dtl files, should that be necessary in processing a correction for time-variable spacecraft-generated magnetic fields. Where necessary engineering data is not available with the required time cadence, interpolation of the engineering data may be required; if interpolation is not feasible, as an alternative, the magnetic field vectors may be averaged and resampled, if necessary. Static spacecraft magnetic fields are compensated via subtraction of a constant (for example, determined from a previous spacecraft roll maneuver, or MAGROLL calibration sequence) that is passed to the analysis program via the input dtl file.

iii. NAIF Kernel Utilities for Ancillary Engineering

The only component on the spacecraft that articulates is the Articulated Payload Platform (APP), since the spacecraft solar arrays and the high gain antenna are all fixed. A moving component or subsystem is a potential source of a variable spacecraft magnetic field, if it has a significant magnetic moment. The APP will be calibrated after deployment (post-MOI) by taking observations of celestial objects in different directions, and before science operations begin, an in-flight magnetic compatibility test will be performed. This test consists of cycling the APP through rotations about the two articulation axes while the magnetic sensors record the magnetic field. In the event that the APP produces a variation in the magnetic field sensed by the magnetometers, an attitude kernel (C-kernel) for the APP will be available for use by the team in applying a correction.

iv. Spacecraft Magnetic Field Mitigation

A static spacecraft magnetic field or instrument offset is measured via periodic spacecraft roll maneuvers and eliminated in data processing either via adjustment of sensor zeros in the instrument calibration file or by insertion of an offset variable in the decommutated telemetry file for each sensor. As of this writing we anticipate that a dynamic correction will be implemented to compensate for the field produced by the solar array, using spacecraft telemetry on switch states and

measurements of the current produced by illumination of the arrays. Implementation of this correction will follow analysis of the in-flight tests planned for execution in the near future. The engineering telemetry necessary for this correction will be passed to the processing program via augmentation of the dtl file. We also anticipate archiving the reaction wheel speeds along with the magnetometer data to avoid confusion with environmental phenomena.

c. Standard Data Products

For immediate use by the science team, and other instrument teams, we provide a quicklook product that consists of time-ordered records of magnetic field vectors in nanoteslas, rendered in spacecraft payload coordinates, along with browse products that are useful in identification of intervals of special interest. These files contain magnetic field processed with a static spacecraft field approximation, but do incorporate the full sensor zeros, calibration scale factors, and sensor orthogonality matrix conversion. These quicklook products are intended for preliminary analysis and planning purposes and are not intended for science archive.

Archive products are produced in a variety of coordinate systems when final reconstructed spacecraft ephemeris and attitude information is available. These include a planet-centered (“pc”) coordinate system, rotating with Mars (z aligned with the spin axis) and with the x axis through the Mars IAU prime meridian; and a sun-state (“ss”) coordinate system wherein the primary reference vector (x axis) points from the object (Mars) to the sun and the secondary reference vector (y axis) is in the Mars orbit plane (approximately opposite to orbital motion) such that the z axis is northward. Both of these coordinate systems are also available with respect to any other body (“object”) of interest, for example, the satellites Phobos and Deimos.

Science archive products are pushed to the SDC on a regular schedule.

VII) Summary

The MAVEN magnetic fields investigation will provide accurate vector magnetic field observations throughout all phases of the mission at sample rates of up to 32 vector samples/s, depending on telemetry allocation. The instrumentation provides two-sensor vector measurements for spacecraft

1003 magnetic field mitigation and complete hardware redundancy for risk mitigation. Magnetic field vectors
1004 are provided in-flight for use by other payloads in optimizing data collection and telemetry utilization.
1005 Spacecraft maneuvers (MAGROLLS) will be performed during science operations approximately every
1006 two months to monitor spacecraft fields and sensor offsets, and a series of additional in-flight tests have
1007 been performed to diagnose and correct for small-amplitude spacecraft-generated magnetic fields. These
1008 data, together with the synergistic particle observations acquired by the PFP instrumentation, and
1009 observations of plasma waves, ultraviolet emissions, and mass spectrometry, will form the foundation of
1010 a comprehensive study of the Mars atmosphere and its evolution.
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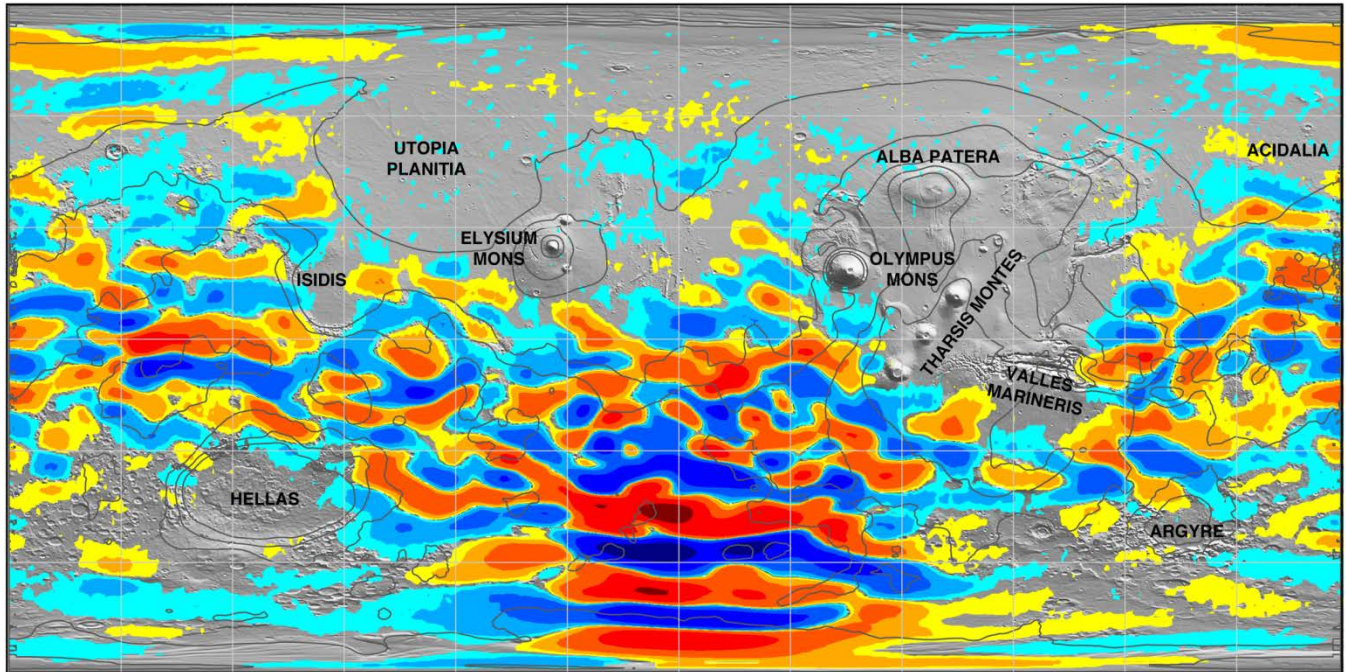
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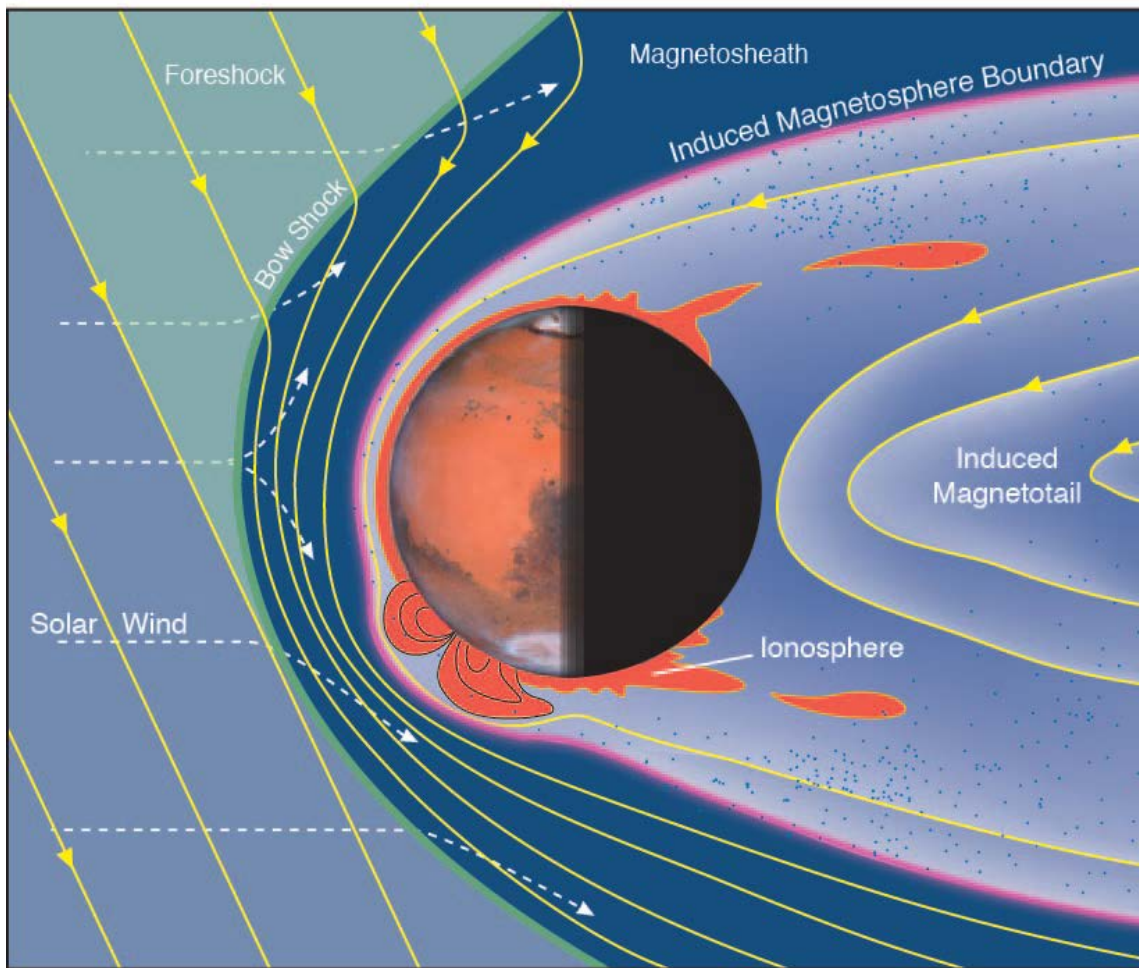
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1121 Figure 1: Map of the magnetic field of Mars observed by the Mars Global Surveyor satellite at a nominal
 1122 400 km altitude (after *Connerney et al.*, 2005). Each pixel is colored according to the median value of
 1123 the filtered radial magnetic field component observed within the 1° by 1° degree latitude/longitude range
 1124 represented by the pixel. Colors are assigned in 12 steps spanning two orders of magnitude variation.
 1125 Where the field falls below the minimum contour a shaded MOLA topography relief map provides
 1126 context. Contours of constant elevation (-4, -2, 0, 2, 4 km elevation) are superimposed.

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1129 Figure 2: Schematic of the solar wind interaction with Mars (from *Brain et al.*, 2014). The solar wind
 1130 carries with it the interplanetary magnetic field (yellow) as it streams (dashed lines) toward the bow
 1131 shock (green) upstream of Mars. Intense crustal magnetic fields (orange) impose structure throughout
 1132 localized regions of the upper atmosphere and ionosphere.

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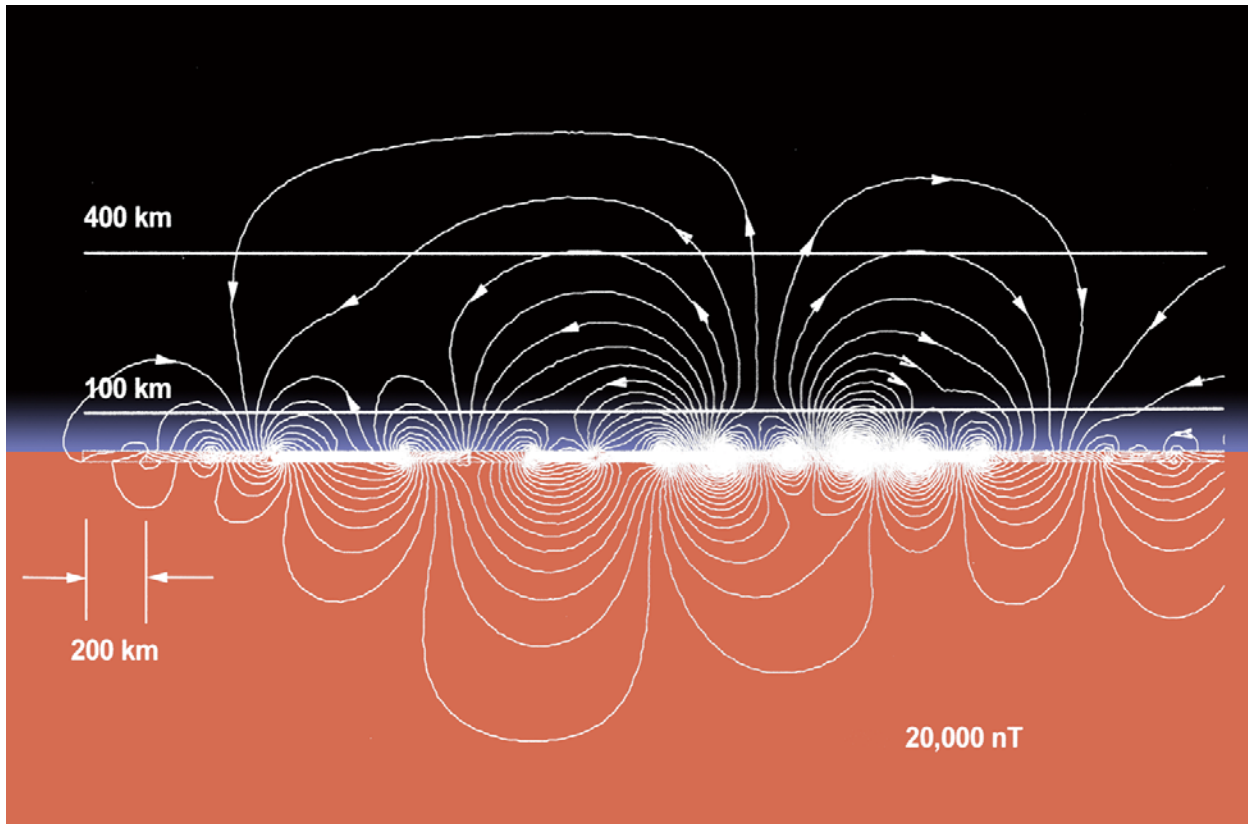


Figure 3: Plane projection of the magnetic field geometry above the intensely magnetized southern highlands based on the crustal magnetic field model of *Connerney et al.*, [1999]. This figure illustrates the field geometry that would be encountered during periapsis passes along a line of constant longitude (near 150 degrees east) and centered at 50 degrees south latitude. Similar “mini-magnetospheres” may be encountered above much of the magnetized crust, depending on spacecraft altitude and solar wind conditions.

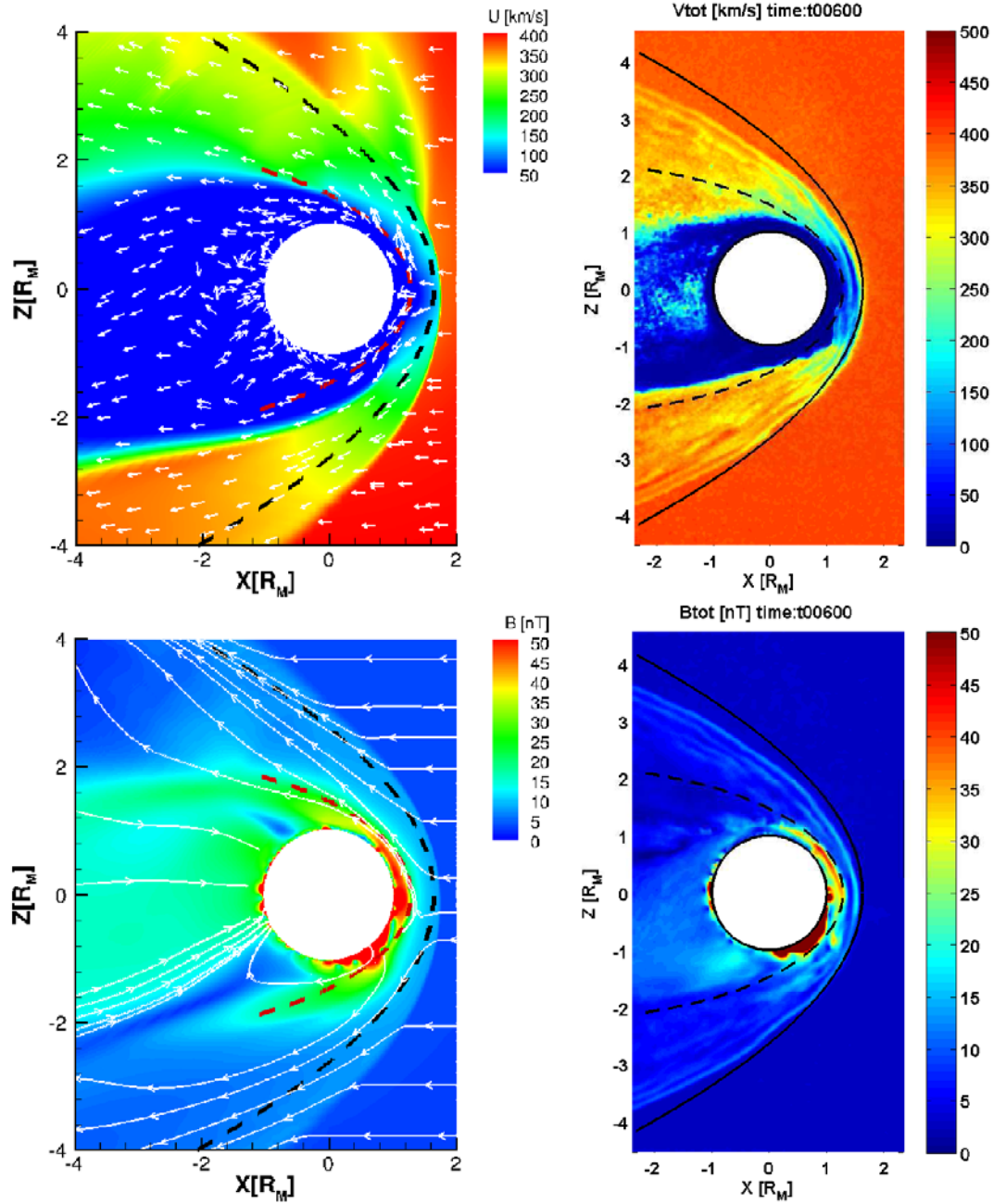


Figure 4: Plasma and magnetic field environment of Mars according to the multi-fluid magnetohydrodynamic simulation of Dong and colleagues [Dong et al., 2014]. Upper left panel is a meridian plane projection of the magnitude (color) and direction (arrows) of plasma velocity near Mars. Lower left panel shows the simulated magnetic field lines and magnetic field magnitude (colors) in meridian plane projection. Large field magnitudes very near the planet's surface are due to strong crustal magnetic fields, primarily in the southern hemisphere, but strong fields due to the solar wind interaction are also encountered at altitude on the day side of the planet.

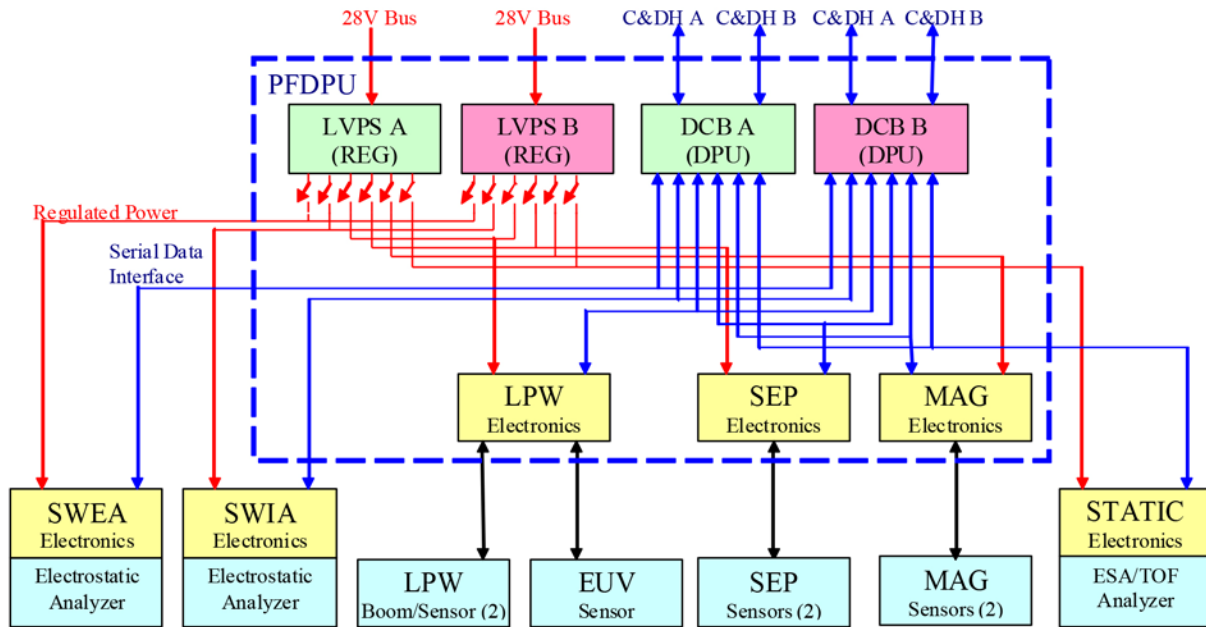
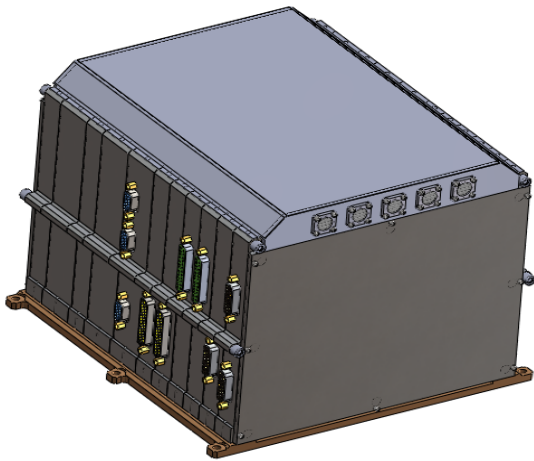


Figure 5: Schematic diagram of the Particles and Fields Package (PFP) and science instrumentation that it services. The PFP Digital Processor Unit (PFDPDU) consolidates instrument power service, command, and telemetry functions for the suite of instruments, presenting a single electrical interface to the spacecraft.



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1162 Figure 6: The Particles and Fields electronics stack, accommodates electronics frames for each of the
1163 instruments in the suite, in addition to redundant power supplies and command and data handling digital
1164 processor units.

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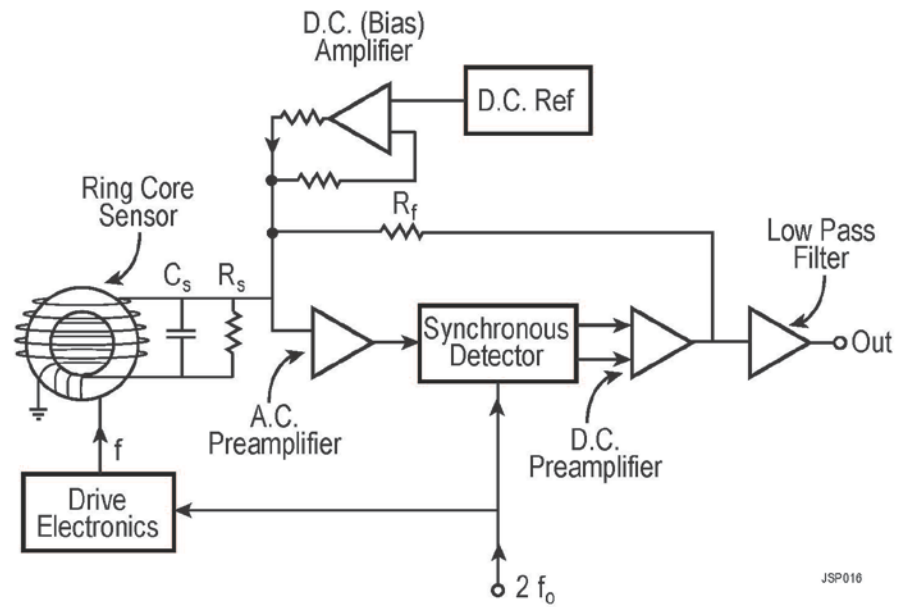
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1170 Figure 7: The MAVEN spacecraft in the clean room at Lockheed Martin during assembly. The (-Y)
1171 MAG sensor (left extremity) is mounted at the end of the MAG “boomlet”. A cautionary piece of yellow
1172 tape hangs below the sensor. The sensor cover bears laminations of copper tape and Kapton tape
1173 providing electrostatic and electromagnetic shielding.

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1177 Figure 8: Schematic of a single-axis fluxgate magnetometer (after Acuña, 2002) utilizing a tuned ring-
1178 core sensor and a shared $2f$ sense and feedback coil.

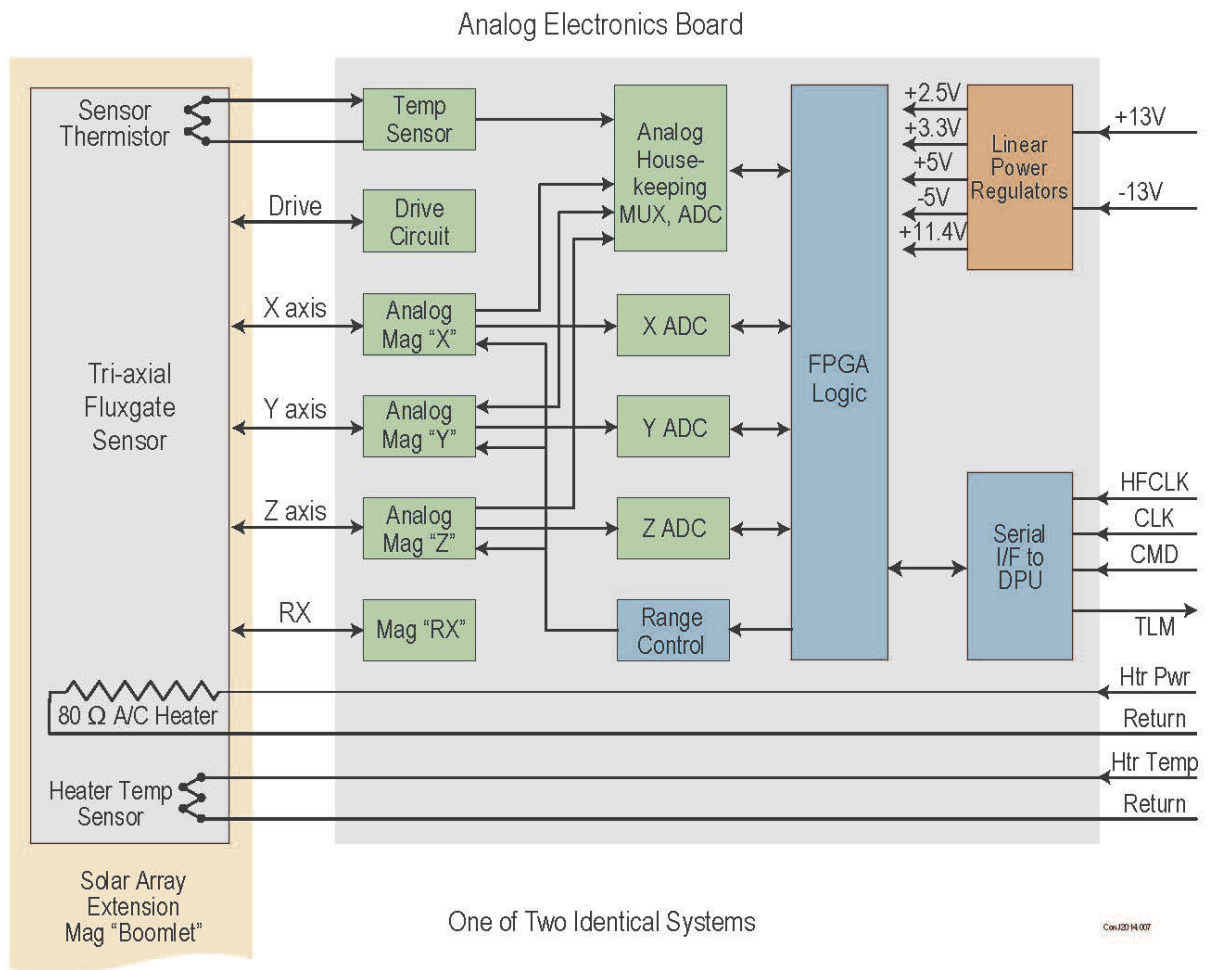
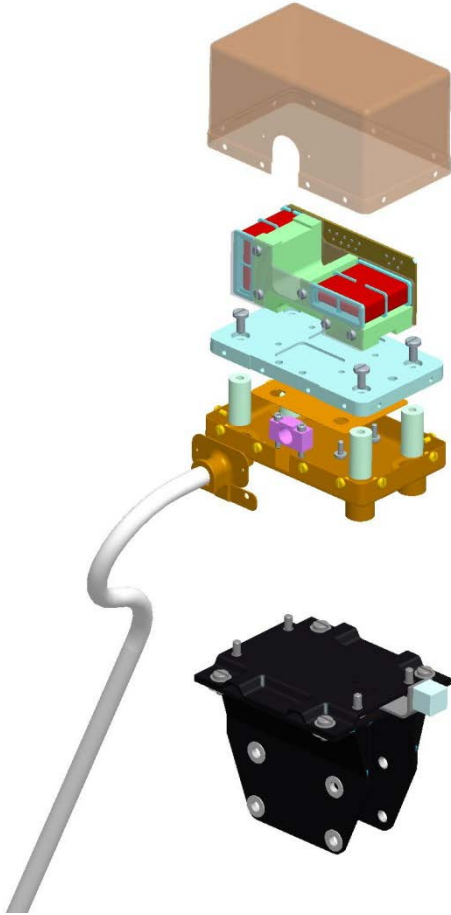


Figure 9: Simplified block diagram of one of the two identical MAVEN vector magnetometers. The tri-axial fluxgate sensor (left) is mounted on the MAG “boomlet” at the end of the solar array and harnessed to the electronics package mounted in the spacecraft body. The analog and digital electronics (right shaded portion) is contained on a single multilayer electronics board that is contained in a shielded enclosure (frame) within the PFP assembly.

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1190 Figure 10: Expanded illustration of the sensor assembly showing the type LE phenolic sensor block
1191 (green), nested sense and feedback coils (red), base (blue), thermal isolation feet (light blue), clam-shell
1192 protective cover (tan), and carbon composite mounting bracket assembly (black) with attached
1193 calibration cube.

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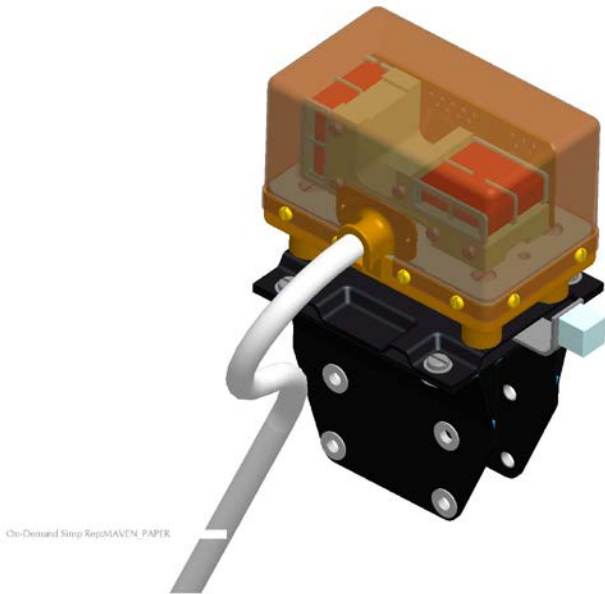
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1201 Figure 11: Photograph of the MAVEN magnetometer sensor assembly showing the phenolic sensor
1202 block (brown), nested sense and feedback coils, and sensor printed circuit board. The sensor is provided
1203 with a (shielded) pigtail connector to insure that interconnect hardware is kept at a sensible distance
1204 from the sensor; nevertheless, all components installed on the MAG boomlets are subject to enhanced
1205 magnetic screening prior to use.

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1210 Figure 12: Assembled sensor assembly. Once assembled, all parts of the sensor assembly remain
1211 assembled except for the lower part of the carbon composite mounting bracket assembly (black) that
1212 attaches to the MAG “boomlet”. The top part of the mounting bracket with the attached optical cube
1213 remains in assembly with the sensor block throughout the entire test and calibration program.

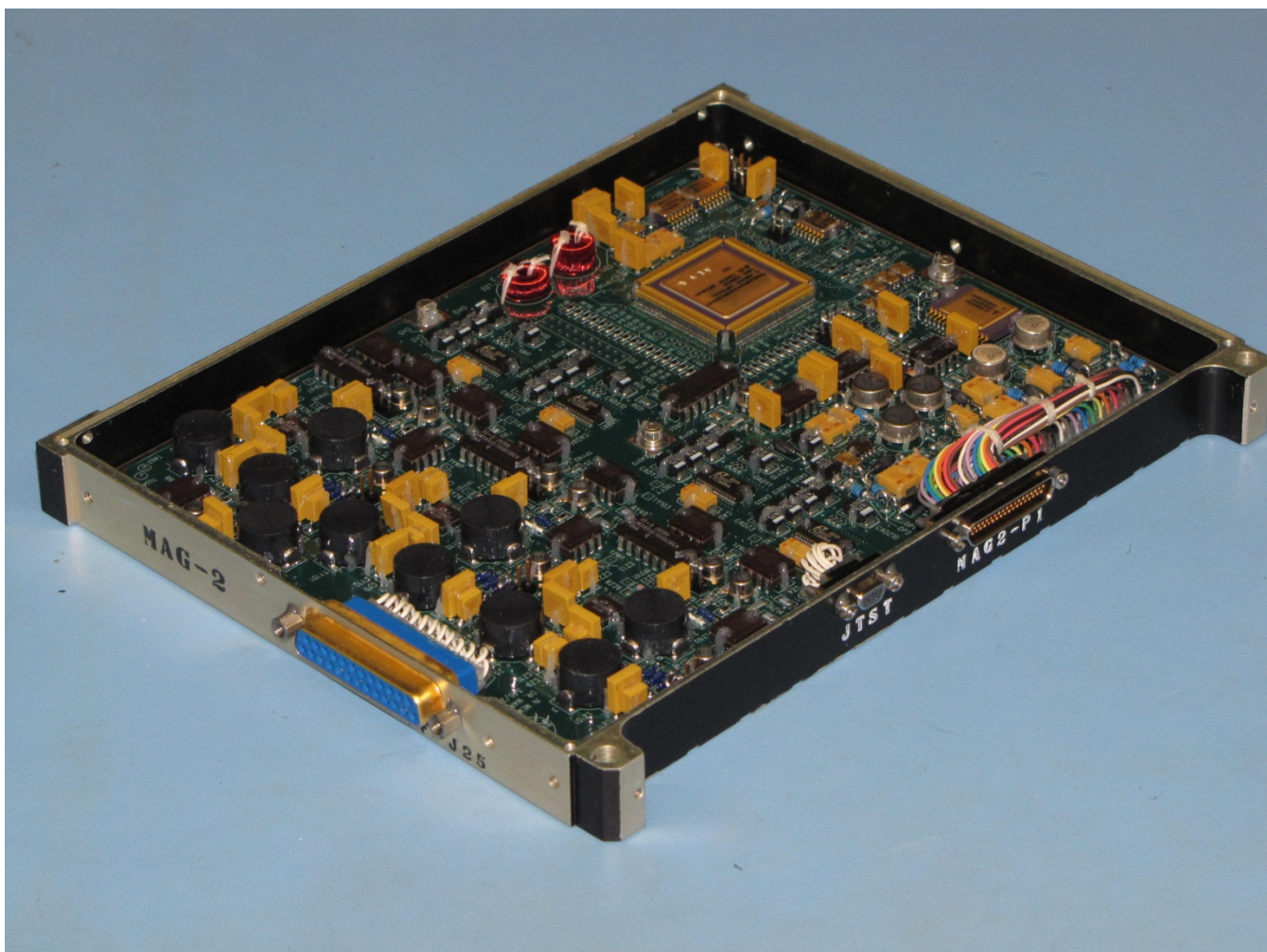
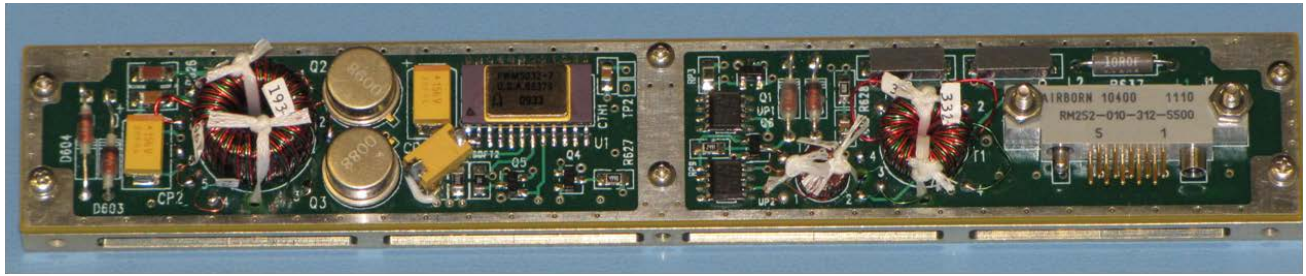


Figure 13: Magnetometer analog and digital board (one of two identical assemblies) in its shielded frame, top cover removed for viewing. The analog portion is to the left, where the sensor cable connector J25 resides, and the digital portion is to the right. The FPGA is the large square device on the upper right.

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1229 Figure 14: Magnetometer a/c heater board (one of two identical assemblies, mounted back-to-back) in
1230 its carrier frame. This assembly is mounted on the PFP instrument interface board.

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Figure 15: Simplified block diagram of one of the two identical MAVEN a/c heater electronics assemblies. The tri-axial fluxgate sensor (left) is mounted on the MAG “boomlet” at the end of the solar array. The heater control electronics (right shaded portion) is contained on a single multilayer electronics board that is integrated with the PFP instrument interface board (in order to minimize potential interference with sensitive analog electronics). A transformer-coupled heater monitor is made available to the spacecraft engineering telemetry so that the thermal power delivered to the MAG sensors may be monitored when the MAG electronics is powered off.

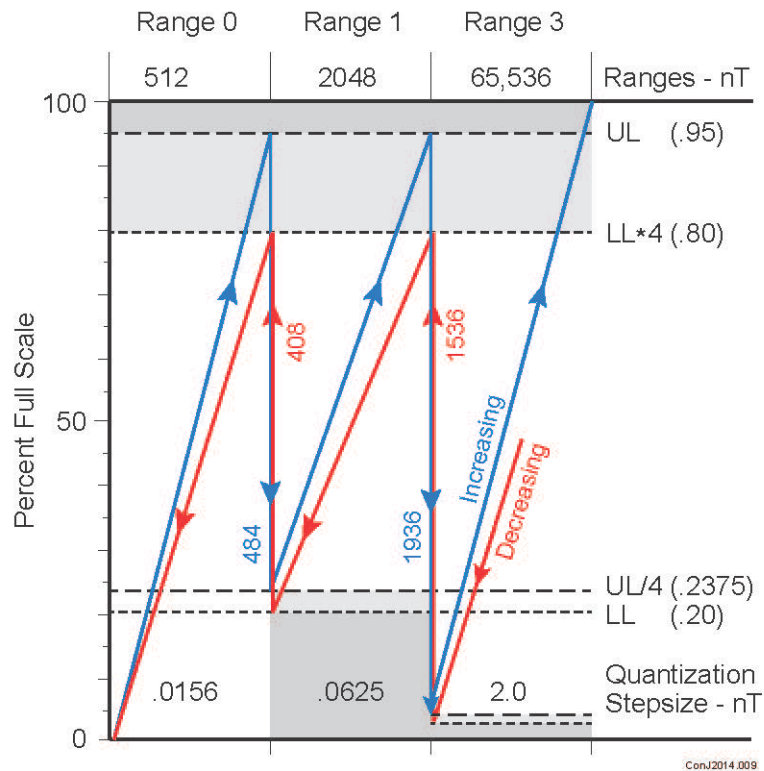


Figure 16: Instrument autonomous range selection algorithm increases the instrument dynamic range to prevent saturation in response to an increasing (blue) magnetic field magnitude in any of the three vector components and decreases instrument dynamic range in response to a decreasing field (red). The algorithm uses “guard bands” to prevent rapid back and forth changes in dynamic range (“toggling”) in the presence of field fluctuations near range limits. Nominal threshold values are shown.

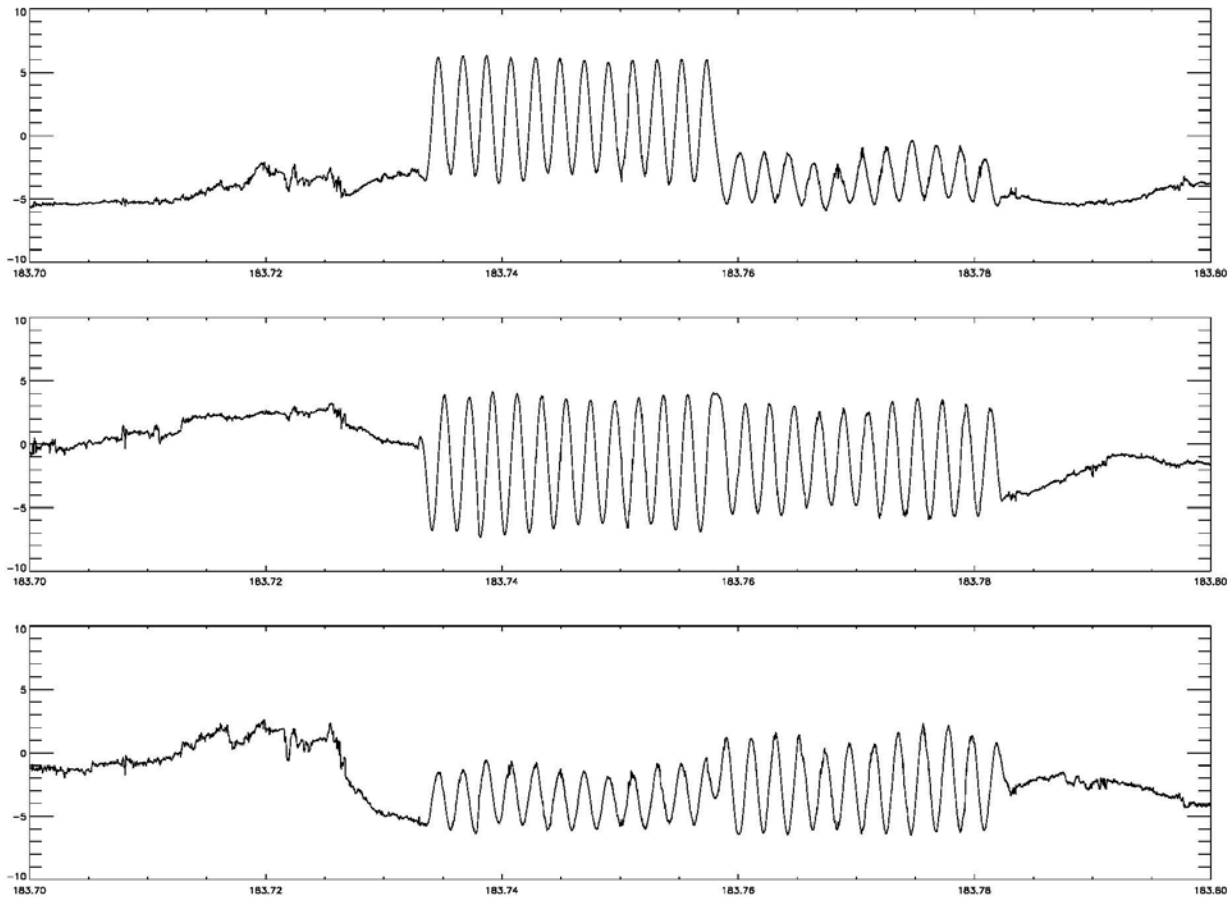
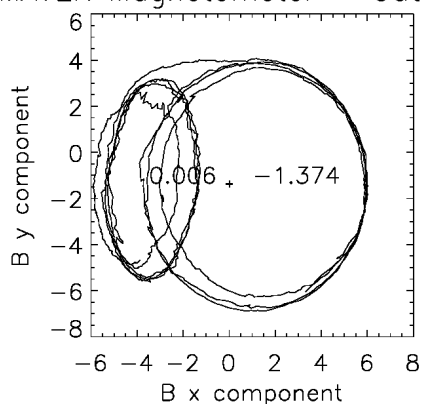
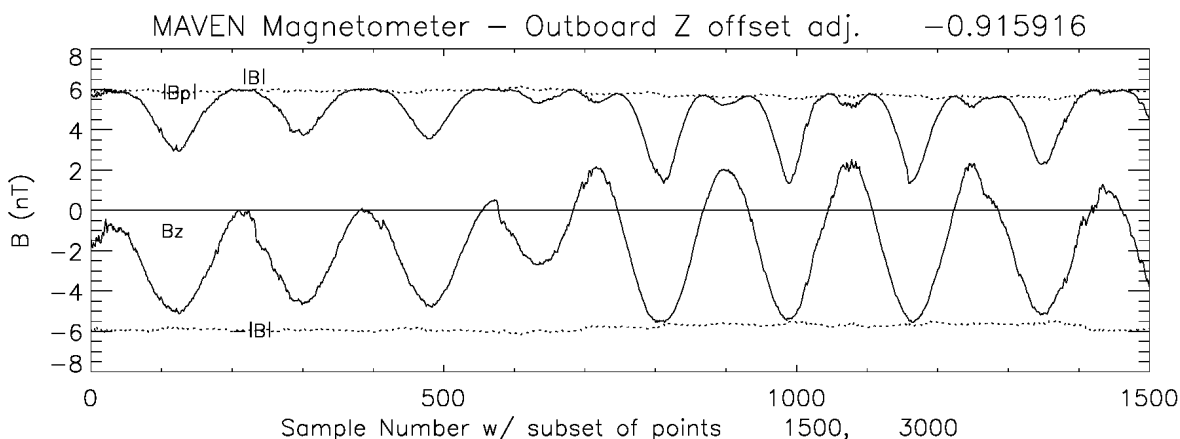


Figure 17: Magnetic field in spacecraft payload coordinates throughout the second cruise MAGROLL maneuver on DOY 183, 2014, during which the spacecraft executes a rolls at 2 degrees/s about a principal axis (near the z axis), followed by rolls about an orthogonal axis (near spacecraft x). Instrument dynamic range was commanded to manual range 1 (± 2048 nT) for the first few rolls about z, followed by rolls about both z and x in range 0 (± 512 nT), followed by rolls about x in range 1. After completion of the sequence, the instruments are returned to autorange mode.

MAVEN Magnetometer – Outboard



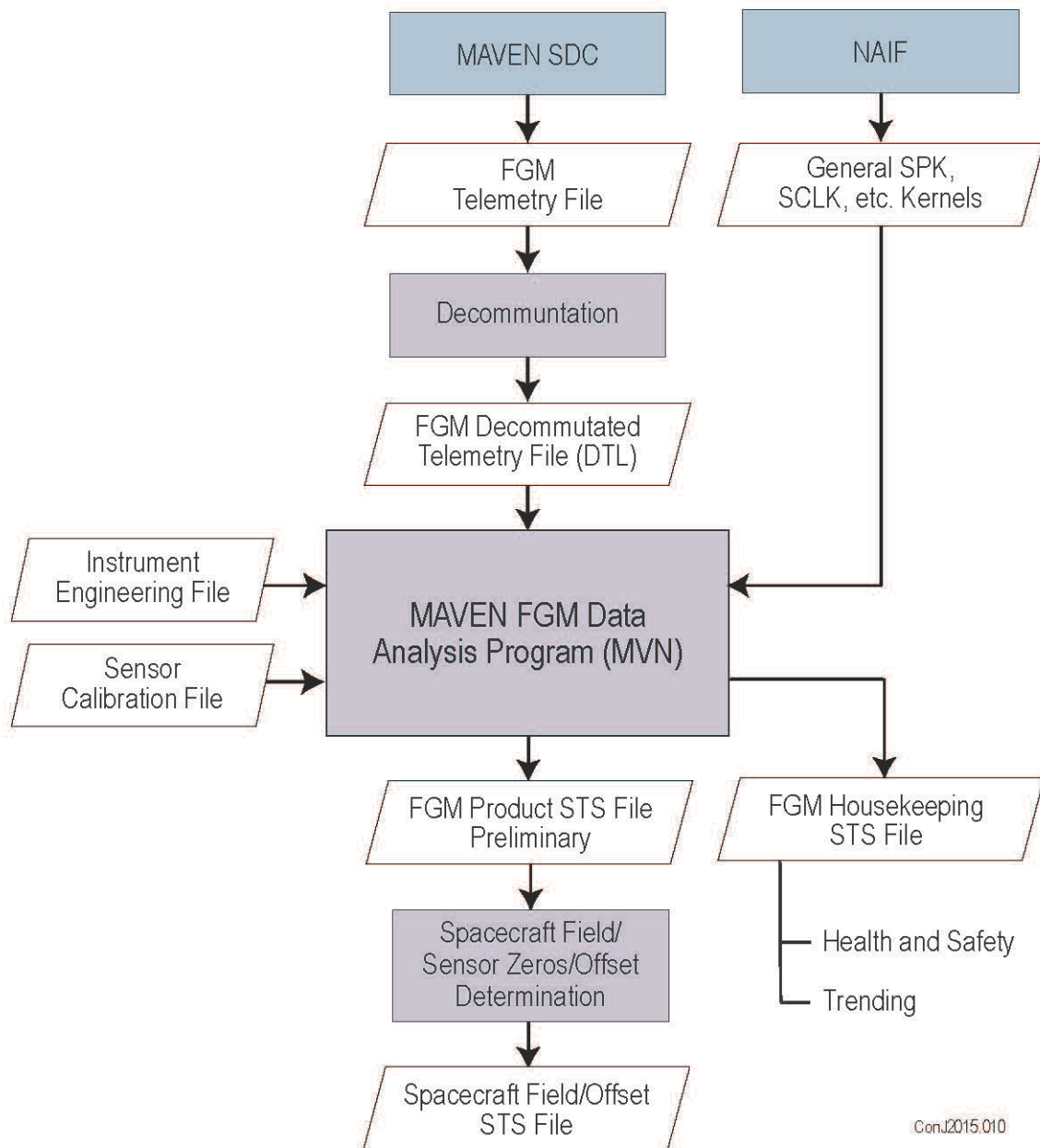
X offset = 0.006
Y offset = -1.374
Z offset = -0.916
range = 0
LAG = 6 seconds
Z offset corrected
magroll_2_pl_sunsc.sts



magroll_2_pl_sunsc.sts

Figure 18: Application of offset estimation to range 0 (+/- 512 nT range) observations obtained during the second cruise magroll exercise, using a six second lag for vector differences, during which the field rotates in the sc reference frame by 12 degrees. The figure in the upper left is a diagnostic hodogram of B_y vs B_x . In the lower figure a time series of the field magnitude and the negative of the field magnitude is shown (dotted line) demonstrating little spin modulation with the estimated offsets applied to the vector observations.

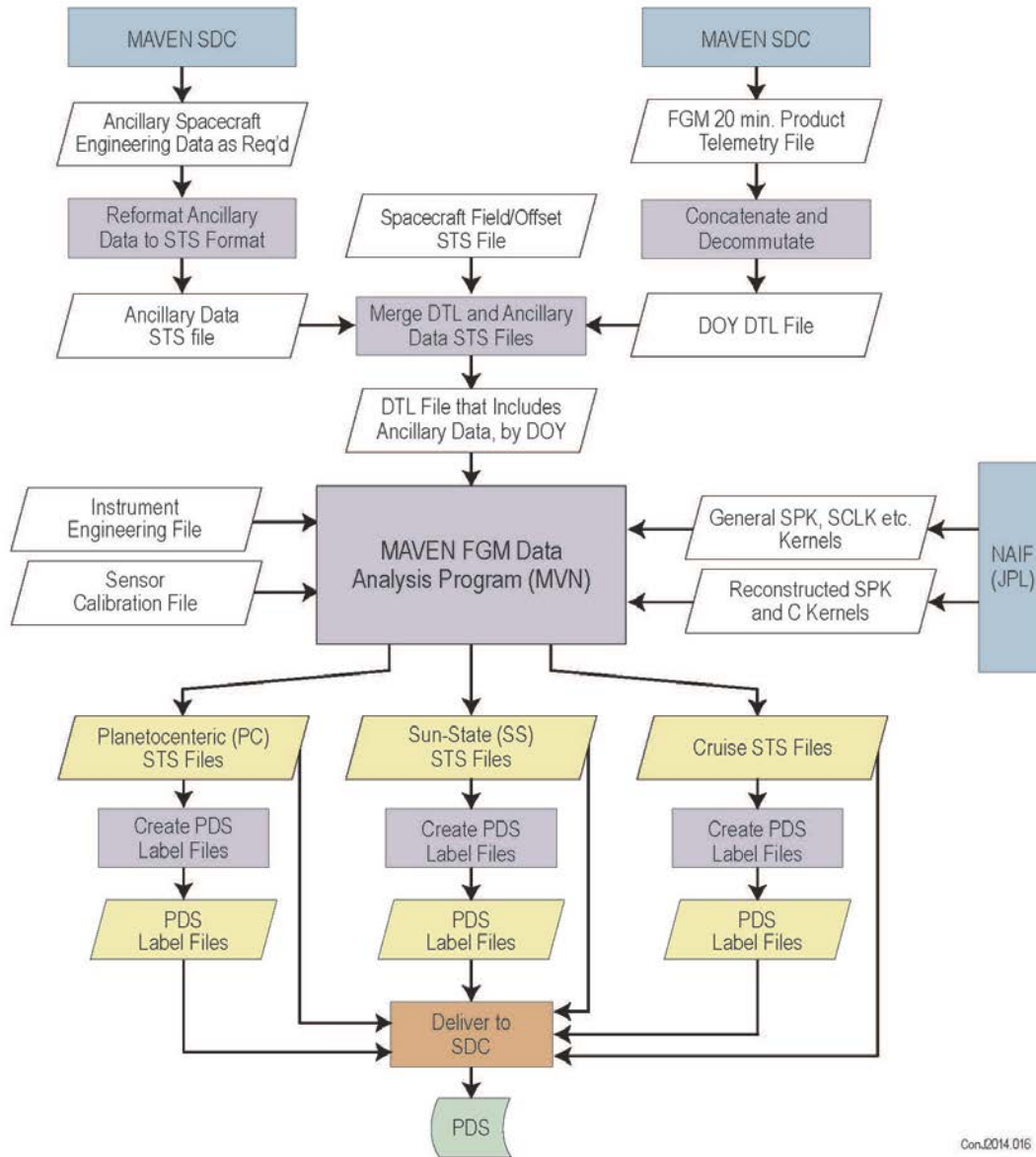
MAG Preliminary Processing



ConJ2015.010

Figure 19: Flow diagram of the preliminary MAG data processing. Preliminary processing is done prior to receipt of supplementary spacecraft engineering data (e.g., solar array currents), reconstructed spacecraft ephemeris, and attitude kernels, to assess instrument health and safety and to estimate sensor zeros and/or static spacecraft magnetic fields.

MAG Archive Processing



Con.2014.016

Figure 20: Flow diagram of MAG final data processing. Final processing is done subsequent to receipt of reconstructed spacecraft ephemeris and attitude kernels using the same program elements. Data files containing time-ordered records of fully-calibrated magnetic field vectors, rendered in several useful coordinate systems, are the archive data products. Each record contains spacecraft position rendered in the appropriate coordinate system along with supplementary engineering data, where useful.